UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

Performance Analysis of the Cellular-V2X Mode 4

A Master's Thesis
Submitted to the Faculty of the
Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona
Universitat Politècnica de Catalunya
by

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In partial fulfilment
of the requirements for the degree of
MASTER IN ADVANCED TELECOMMUNICATION TECHNOLOGIES

Advisor: Jordi Pérez Romero

Barcelona, July 2020

Title of the thesis: Performance Analysis of the Cellular-V2X Mode 4

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Abstract

Vehicular communications are becoming a reality and are necessary to improve safety driving conditions. The objective of this thesis is to introduce the basic concepts of Cellular-V2X Mode 4 and analyze its performance in terms of channel busy ratio (CBR) and packet delivery ratio (PDR) under different scenarios and configurations. A C-V2X Mode 4 Simulator has been used to check the impact of different parameters such as the transmission rate, modulation and coding scheme, transmission power, subchannelization or probability of keeping the granted resources among others. Two different scenarios have been considered, a fast highway and a congested highway with low speed and high vehicle traffic congestion. The results have revealed relevant differences in terms of PDR between both scenarios. The main causes of failure, the delay and CBR have been also analyzed. The transmission rate is the parameter that most influences the overall performance of the network. In some cases such as the congested highway scenario, obtained performance has revealed some limitations of the technology, e.g. in terms of PDR... and it is expected that with the new capacities of 5G NR it could be improved.

I would like to thank all my family, my girlfriend and my friends the support shown during all these months. Especially thanks to my project director Jordi Pérez Romero who supported me greatly and was always willing to help me.

Acknowledgements

Thanks to Jordi, who has been a great director that has offered support always that I needed it and has helped me to go through the difficulties that appeared during the thesis development. I want also to say thanks to Brian McCarthy (b.mccarthy@cs.ucc.ie) PhD student from University College Cork (Ireland) and developer of the Open C-V2X – Mode 4 implementation for the altruistic support shown during all these months. Brian was always willing to hear my doubts about the code implementation and possible errors found during the simulations.

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Revision history and approval record

Revision	Date	Purpose
0	22/05/2020	Document creation
1	16/07/2020	Document revision

Written by:		Reviewed and approved by:	
Date	15/07/2020	Date	16/07/2020
Name	Daniel León Gonzalez	Name	Jordi Pérez Romero
Position	Project Author	Position	Project Supervisor

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1. Introduction

1.1. Motivations

During the last decade, the developments around cellular communications and the automotive industry have grown considerably. The new imposed safety requirements as well as the goal to achieve the well-known full autonomous cars, have triggered a research line over cellular communications and how important are going to be in the race to reach the perfect full autonomous car.

Within this context, a new term to cover all these requirements has appeared. Vehicle to everything (V2X) is the way to define how a car interact with any other system or item. When the communication is with another vehicle it stands for V2V (Vehicle to Vehicle), with an infrastructure is V2I (Vehicle to Infrastructure), with a pedestrian is V2P (Vehicle to Pedestrian) and finally the communications between the vehicle and the network is defined as V2N (Vehicle to Network). In order to fulfill the requirements established by V2X communications, the Third Generation Partnership Project (3GPP) has developed the so-called Cellular V2X (C-V2X) which relies in standardized mobile cellular communications by the same 3GPP such as 4G LTE or 5G.

1.2. Objectives

Nowadays, the main mobile cellular technology that is being used for C-V2X purposes is 4G LTE. Specifically, the LTE Release 14 has included the support for C-V2X use cases and it is usually referred to as LTE-V. There are two communication modes known as mode 3 and mode 4. The baseline is mode 4 since represents that the operation without cellular coverage is possible, and then the V2V communications can be performed directly between vehicles without the necessity of having a base station that is managing these communications. We can refer to this way of communications as C-V2X Mode 4.

The main objective of this work is to perform an analysis of the C-V2X Mode 4. The focus will be put in Mode 4 instead of Mode 3 because V2V safety applications should not depend on the availability of a base station (i.e. infrastructure based cellular network). Since vehicles can autonomously select their own resources operating under Mode 4, this mode is the most suitable for V2V applications. With help of a simulator of the technology, the impact of selecting different key parameters of the standard and different scenarios is going to be analyzed. With the obtained results, the limits of this technology, the weaknesses and the strengths can be defined.

1.3. Methodology

To achieve the aforementioned objectives, the first step was to increase the knowledge about C-V2X. This is why section 2 is intended to do a presentation of the technology. A description of the two main technologies that are actually used for vehicular communications will be described. It will also contain a deep description of how C-V2X Mode 4 works and which are its main characteristics. Finally, a brief description of which is the vision and the role about V2X communications using 5G as the cellular technology.

A simulator of the C-V2X Mode 4 technology that consists in different software is used to simulate different scenarios under different configurable parameters that have been studied in section 2. In section 3, the software is presented within the range of configurable parameters and the base configuration that will be used for all those parameters that are not going to be changed. How the statistics are collected and managed as big data from the simulations is also explained. Finally, the different scenarios that were considered during the simulation

The section number 4 is where the performance analysis of the technology is performed. It is divided in different subsections depending on which is the parameter that is being studied.

Finally, the last section is a summary of all the thesis and which are the future works that can be done to continue what I have done.

1.4. <u>Work Plan</u>

The thesis development had a total duration of 5 months, starting February 16th, at the beginning of the 2nd semester of the 2019/2020 academic year and finishing at July 16th. In **Figure 1.1** the work plan represented as a Gantt chart can be observed. During the thesis development three different Work Packages (WP) were established: the WP1 C-V2X Mode 4 Study, WP2 Simulation and WP3 Results.

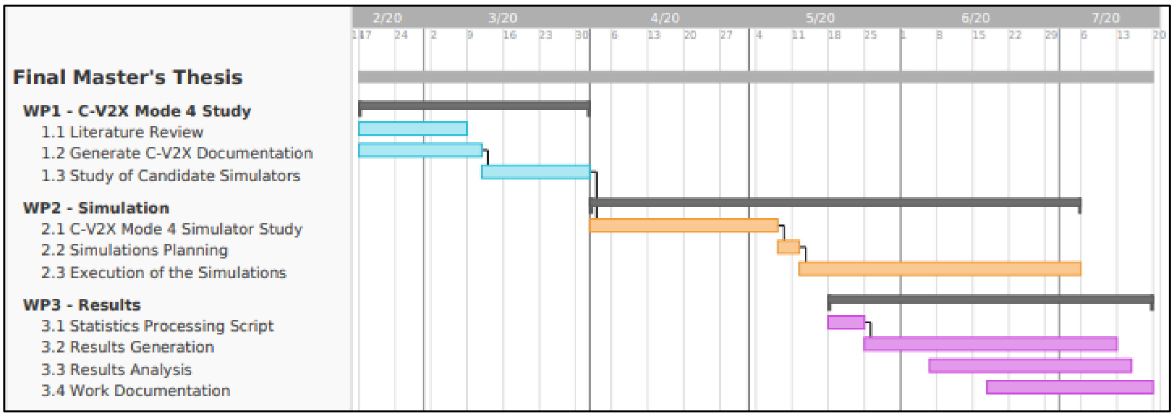

Figure 1.1 Work Plan

<u>**WP1 – C-V2X Mode 4 Study**</u>: During the first month and a half, a deep study of the Cellular-V2X Mode 4 was performed. This WP was organized in the following tasks:

1.1. <u>Literature Review</u>: Review of the literature such as papers and some sections of the C-V2X standard.

1.2. <u>Generate C-V2X Documentation</u>: Simultaneously with the task 1.1 and mainly to reduce the final documentation load, some documentation was generated.

1.3. <u>Study of Candidate Simulators</u>: The last three weeks of March were dedicated to perform an analysis of the different simulators, the possibilities that offer with respect to C-V2X Mode 4, the types of simulations, the results and the configurable parameters.

WP2 – Simulation: The main intention of this work package is to perform all the actions related with the simulations. This work package lasted three months, almost until the end of the thesis development, and was organized in the following tasks:

2.1. C-V2X Mode 4 Simulator Study: Once the simulator and how it implemented the C-V2X Mode 4 was understood, it was necessary to study how to configure the parameters and create my own simulations.

2.2. Simulations Planning: During one week the different scenarios and types of simulations were decided.

2.3. Execution of the Simulations: The last task of this work package and the longer one took almost two months. During these two months, different problems appeared, several initial planed simulations had to be changed and re-simulated. During this time, it was necessary to exchange some emails with the developer of the simulator to clarify and fix some aspects of the simulator since it was in its early development stages. To perform the simulations, I had to use a virtual machine with Ubuntu since with Windows there was a kind of bug. The virtual box performance was kind of poor since it was using half of the resources of my computer which at the same time it is not so powerful. Because of this reason and the aforementioned problems, the simulation phase took a long time.

WP3 – Results: The last work package started only a week after the second one and it lasted until the end of the thesis development. This WP was organized in the following tasks:

3.1. Statistics Processing Script: Design of a python script able to process the raw data generated by the simulator

3.2. Results Generation: Generation of the result files by using the processed data by the script.

3.3. Results Analysis: Analysis of the generated files to generate charts and extract valuable conclusions.

3.4. Work Documentation: The final task was to document all the results and the gather all the relevant information in a document.

2. Cellular Vehicle to Everything Communications (C-V2X)

2.1. Introduction to vehicular communications

The evolution of the automotive industry towards near-perfect safety driving conditions and the desired full autonomous driving has required from a new research area in wireless communications. Vehicular communications systems are the answer to this evolution needs. It is important to mention that along with the vehicular communications systems, the electronics, sensing technologies and computing techniques (machine learning and computer vision) are important to achieve the use cases.

Vehicular communications are based on networks where the cars are considered nodes and may interact with other nodes known as vehicle to everything (V2X). These other nodes can be pedestrians (V2P), infrastructures (V2I), other cars (V2V) or simply internet based networks (V2N) **(Figure 2.1)**. The nodes in this network must cooperate to exchange information such as traffic info and security advertisements. The idea of this perfect safety driving conditions can be reached thanks to this network and its cooperative work way. When the nodes cooperate, this can help to avoid road accidents between vehicles, hit pedestrians, notify about traffic jams to reduce the speed with enough time and even clear the path for emergency services in high loaded roads. This network must be implemented with a wireless communication technology. There are two main technologies with its strengths and weaknesses that are being considered.

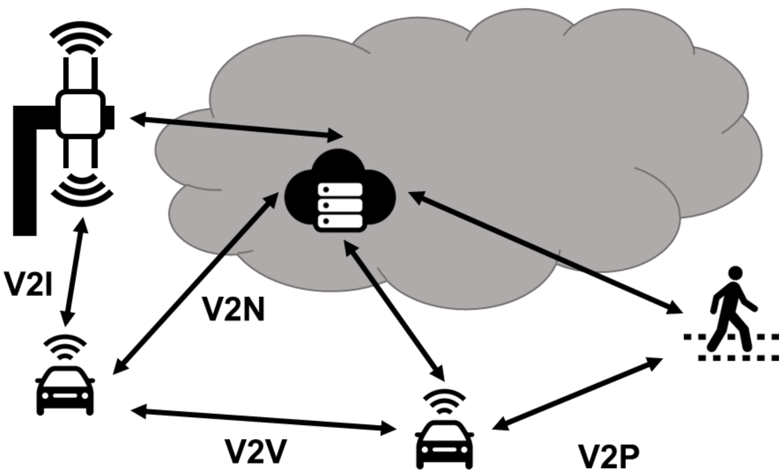

Figure 2.1 V2X Types

The first technology that is considered is based on the IEEE 802.11p standard and it is known as Direct Short Range Communications (DSRC) [1]. The DSRC standard has been completed in 2009 so a lot of car manufacturers and stakeholders in general, had enough time to perform tests. The United States of America is pushing very hard to implement DSRC as the technology used for V2V applications that require critical latency around 100 ms, very high reliability and security in the 5.9 GHz band (5.850 – 5.925 GHz). However, the initial intention of DSRC was to transmit short-range (around 300 m) basic safety messages between vehicles and therefore it is not intended for high bandwidth requirements of V2N applications. In addition, considering the way that the standard was developed, it is not possible to improve the standard in order to meet the new advanced requirements that are being considered nowadays.

The second technology considered and the one that concerns the study of this thesis, is known as C-V2X or LTE-V and it is based on the 3GPP LTE Release 14 standard [2]. Unlike in DSRC this technology is able to meet the new requirements and the customer needs. Some of this requirements include road safety related use cases (e.g. emergency stop, road safety services, queue warning…), mutual vehicle awareness related use cases (e.g. forward collision warning, emergency vehicle warning…) and finally vehicle related application use cases (e.g. automated parking system or remote diagnosis) [3]. An example is that it has evolved from the LTE Release 12 proximity services (ProSe) [4]. The ProSe were addressed to public safety and some V2V communications. However, the rapid evolution of the requirements ended in the new LTE Release 14 feature called Device-to-Device (D2D) communications which is an evolution of ProSe. Mainly it was designed with the objective of prolonging the battery lifetime of the device with the consequence of increasing latency. For obvious reasons, these objectives are not suitable for V2X communications. In fact it is not until the Release 14 that all the V2X requirements are met. For future releases, in the scope of 5G NR it is expected to be presented the enhanced V2X (eV2X) which will met new and advanced use cases.

2.2. LTE-V for V2X communications

The main objective now is to describe which the main characteristics of LTE-V are and how it works in order to meet the requirements of the V2X communications.

When in LTE Release 12 the support for D2D communications was introduced, three different scenarios were considered. One where the devices where both in coverage, another where one was out of coverage and the other under coverage and finally one were none of the devices were under coverage. In addition to the classical well known uplink and downlink link types, one new was defined to manage the direct communications between devices known as sidelink (SL). The SL has been also adopted in Release 14 to support the V2X communications. Therefore, for LTE-V we can find two different interfaces for V2X communication **(Figure 2.2)**:

- **E-UTRAN Uu radio interface:** This is the cellular interface that is present in all LTE systems. It is an interface between the evolved Node B (eNB) and the user equipment (UE). The communications over this interface are unicast type and held by the classical physical channels of LTE (i.e. PUSCH/PDSCH). This interface supports V2I communications.
- **PC5 interface (V2X sidelink):** This new interface is in charge of the support of direct communication between vehicles (i.e. V2V) based on the LTE SL. This interface supports multicast/broadcast communications since one vehicle can report a message to other vehicles through this interface.

Both interfaces can be used simultaneously and independently one for transmission and the other for reception.

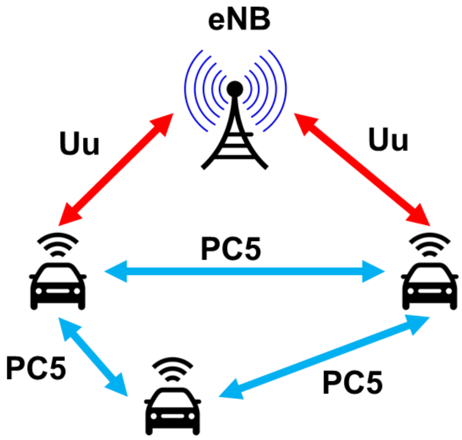

Figure 2.2 V2X Communication Interfaces

When the D2D communications were initially designed, two different operation modes named mode 1 and mode 2 were also defined for using through the LTE SL. Each of the modes was intended for public safety transmissions and their main objective was to improve the battery of the devices when they were out of coverage with the consequent cost in terms of latency. When the LTE-V standard was designed to fulfill the V2X requirements, an evolution of these two original modes originally designed for the ProSe services was performed to meet the requirements of the V2X SL.

As a consequence, LTE Release 14 included two new modes to support the communication for V2V which are based in these original modes for D2D communications. These modes are mode 3 and mode 4 **(Figure 2.3)**, both of them are essentially communication options over the sidelink, so the PC5 interface:

- **Mode 3:** When the vehicles are operating in mode 3, the cellular network, thus the eNB is the one that selects and manages the radio resources used by vehicles in V2V communications through the Uu interface. It assigns dynamically which are the resources that each of the vehicles must use to communicate between them over the PC5 interface. These resources must be requested by the UE (in that case the vehicle) to the eNB. For obvious reasons, this mode is only available when the vehicles are on coverage.

- **Mode 4:** This mode is the most important one and it is considered the baseline mode of LTE-V and it the one that is going to be considered in this thesis. This mode is the direct competitor of the IEEE 802.11p DSRC protocol. When the vehicles are operating in mode 4, they select autonomously the radio resources for their direct V2V communications. It works with a distributed scheduling scheme for vehicles to select their radio resources from specific resource pools. It also includes the support for distributed congestion control. Thanks to mode 4, the vehicles can operate without coverage, thus without the support of an eNB.

Before introducing some characteristics of the operation mode 4, a description of the physical layer which has some similarities with LTE base mode and the organization of the radio resources is given. The main characteristics can be summarized as:

- **Transmission scheme:** Single Carrier Frequency Division Multiple Access (SC-FDMA). When the V2V communications are performed over the PC5 interface, the deployments usually consider a unique carrier located in the 5.9 GHz band.

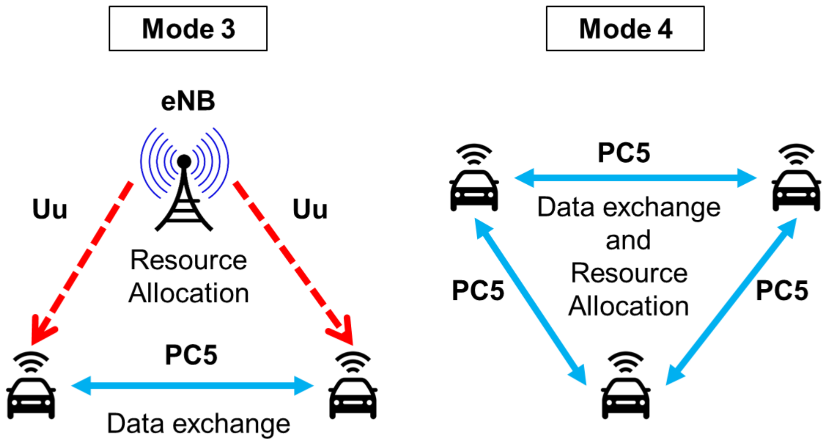

Figure 2.3 V2X Communication Modes

- **Channelization:** 10 MHz and 20 MHz channels.
- **Channel division:** Each channel is divided into subframes (time), resource blocks (RBs) and subchannels (frequency).
- **Subframes:** One subframe is 1 ms long. One subframe contains 14 symbols.
- **Resource block:** It is defined as the smallest unit of frequency resources that can be allocated to a user. One RB occupies 180 kHz and contains 12 subcarriers which implies 15 kHz subcarrier spacing. The total number of RBs that a channel contains is 50 for 10 MHz and 100 for 20 MHz channelization.
- **Subchannel:** A certain group of RBs in the same subframe. The channel then can be defined as a certain number of subchannels with a given number of RBs/subchannel. The subchannel is used to transmit data and control information.
- **UE properties:** A maximum transmission power of 23 dBm. A sensitivity at receiver of -90.4 dBm.
- **Modulation and coding schemes:** The modulation that can be used is QPSK or 16QAM when it is about data transmission and QPSK when it is for control information transmission. Turbo coding and normal cyclic prefix is used.

The V2X sidelink transmission scheme is the same one as the UL one in LTE. However, there are some differences. The symbol configuration in LTE included two De-Modulation Reference Signals (DMRS) and a Sounding Reference Signal (SRS) in every 14 symbols (i.e. 1 subframe). The symbol configuration for V2X sidelink **(Figure 2.4)** incorporates two changes. To cope with the high Doppler Effect associated to the high frequency band of 5.9 GHz, two more DMRS are added having a total of four DMRS in every subframe. In addition, the SRS is deleted and the last symbol of the subframe that was occupied by it is left blank to allow the vehicle to change between transmission-reception modes and timing adjustment.

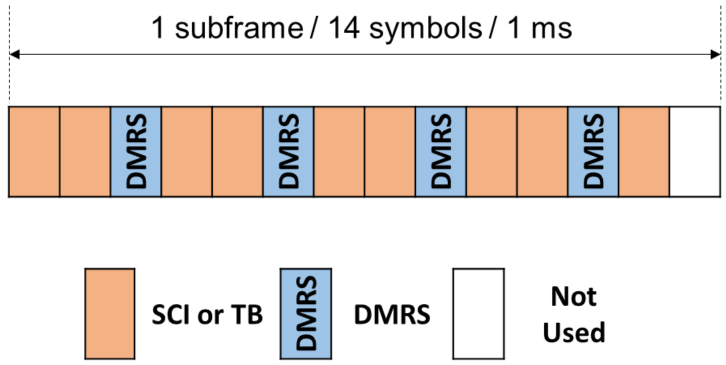

Figure 2.4 V2X Sidelink Symbol Configuration

LTE-V defines two different physical channels that are used depending on which is the content that it is transmitted. The control information is known as Sidelink Control Information (SCI) and it is transmitted through the Physical Sidelink Control Channel (PSCCH). The data is transmitted in Transport Blocks (TBs) which contain the full packet to be transmitted over the Physical Sidelink Shared Channel (PSSCH). The data packets, can be transmitted every 100 subframes, thus 10 packets per second (pps), and also can be transmitted in multiples of 100 subframes with a minimum of 1 pps. Higher transmission rates such as 20 pps and 50 pps are also considered by the standard. The SCI (also known as scheduling assignment) includes information about the Modulation and Coding Scheme (MCS) used to transmit the TBs, how many RBs it uses for the transmission and the Resource Reservation Interval (RRI) for the Semi Persistent Scheduling (SPS) which will be explained later. As a consequence, it is critical that the SCI is received correctly since the other vehicles will need this information to decode correctly the TB with the data associated.

When any vehicle wants to transmit a TB it must transmit its associated SCI. The transmission of this pair is usually known as SCI+TB and it must be transmitted always in the same subframe, so simultaneously in time. Nevertheless, LTE-V defines two subchannelization schemes **(Figure 2.5)** to perform the transmission of the SCI+TB pair.

- **Adjacent PSCCH + PSSCH:** In this scheme the SCI+TB pair is transmitted in adjacent RBs. The SCI occupies always the first two RBs of the first selected subchannel by the vehicle. The TB is transmitted in RBs following the SCI. Depending on its size, the TB can occupy more than one subchannel. If this is the case, it will be able to occupy the first two RBs of any of the extra subchannels that it needs.

- **Non Adjacent PSCCH + PSSCH:** In this scheme, the SCI+TB pair is transmitted in non-adjacent RBs. The frequency-time scheme is divided in pools. One pool is dedicated only to transmit the SCIs (always occupying only two RBs). A second pool is reserved to transmit only TBs and it is divided into subchannels.

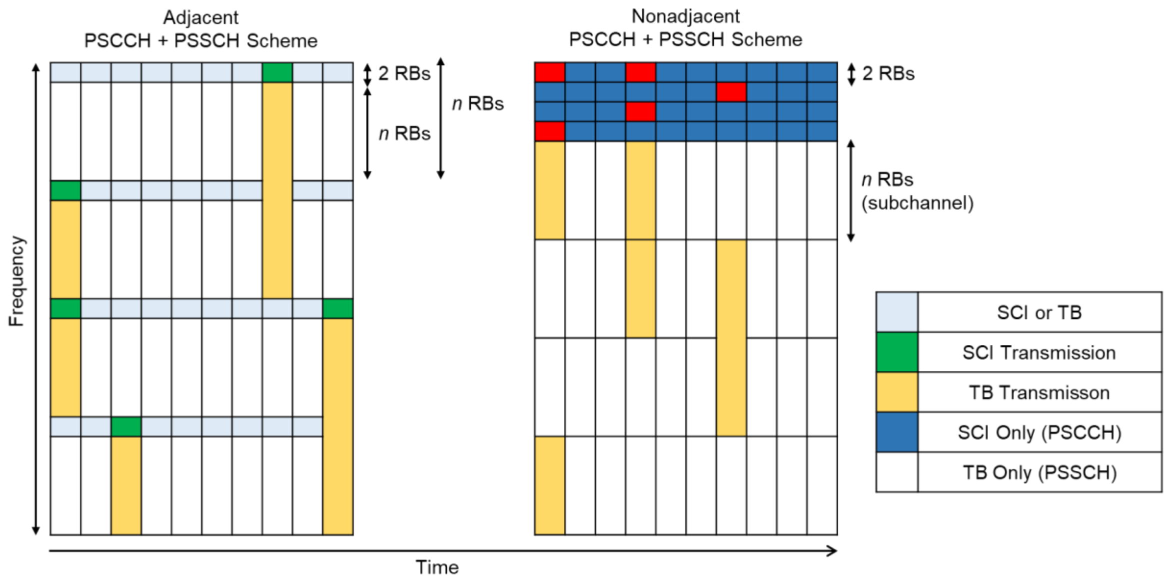

Figure 2.5 LTE-V Subchannelization Schemes

2.3. V2V Communications through Mode 4

In this section a more detailed description of the C-V2X Mode 4 is provided, the main characteristics and how the resources are autonomously selected by the vehicles is provided. As it has been mentioned previously, independently that the vehicles are under cellular coverage or not, the vehicles select autonomously their radio resources. However, if they are under cellular coverage, the network decides the configuration of the V2X sidelink channel. It decides some configurable parameters such as the carrier frequency, the resource pool, the subchannelization scheme, subchannels, RBs per subchannels… and informs the vehicles through the Uu radio interface. When this is not the case and the vehicles are not under cellular coverage, they configure the V2X sidelink with a set of preconfigured parameters.

2.3.1. Sensing-Based Semi Persistent Scheduling

When the vehicles are operating under Mode 4, they select the subchannels that are going to use through the sensing-based SPS scheme **(Figure 2.6)** which is performed at MAC layer. The SPS procedure work as follows:

- Let's suppose that a vehicle, needs to reserve new subchannels at a time T_1. It can reserve subchannels between T_1 and T_2, where T_2 represents T_1 plus the latency constraint of the application that should be equal or less than 100 ms. Note that T_2 and as a consequence the selection window, will last 50 and 20 ms for 20 and 50 pps transmission rates respectively. The time period T_1-T_2 is defined as the selection window. Within this selection window, the vehicle identifies the Candidate Single-Subframe Resources (CSRs) also known as candidate resources. A CSR consists of a set of contiguous subchannels in a single subframe. The number of subchannels *L* depends on the message size.
- The vehicle, analyzes all the information it has received in the 1000 subframes before T_1 known as sensing window. It initializes two lists L_1 and L_2. L_1 initially contains all the CSRs in the selection window. L_2 it is declared as an empty set.

- The vehicle excludes from list L_1 the CSRs for which in the sensing window it has correctly received an SCI indicating that it will utilize the given CSR at the same time.
- The vehicle defines a threshold *Th* and measures the average Reference Signal Received Power (RSRP). All the CSRs where a PSSCH RSRP measurement is higher than *Th* are excluded.
- If the remaining CSRs represent less than the 20% of the total initial resources, the threshold *Th* is increased by 3 dB and the two previous steps are repeated.
- Finally, when the list L_1 contains at least the 20% of the total initial resources it includes in list L_2 all the CSRs from L_1 that experienced the lowest average Received Signal Strength Indicator (RSSI) over all its RBs. This list is reported to higher layers and MAC randomly selects a candidate resource from the list for the first transmission.

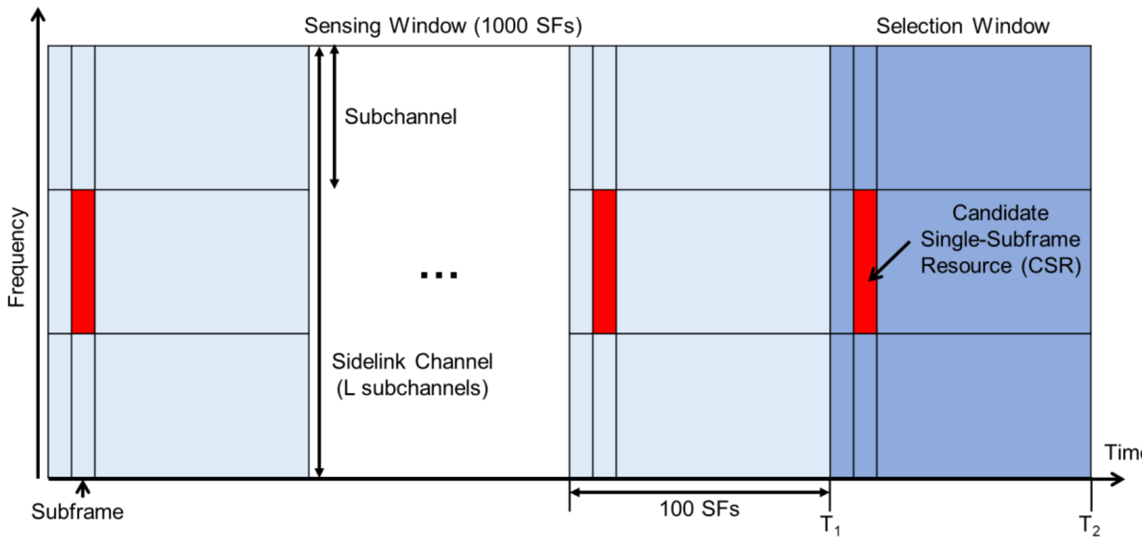

Figure 2.6 Semi-Persistent Scheduling in C-V2X - Sensing and Selection Window

LTE-V Mode 4 provides the option for each packet to be transmitted twice to increase reliability. In that case a third list L_3 is made of all the candidate resources included in L_2 that are in the interval [*SF* – 15 ms ; *SF* + 15 ms] where *SF* is the subframe where the original transmission of the pair SCI+TB took place. For obvious reasons, the CSRs in subframe *SF* are excluded.

The SPS grant persists for a limited amount of time. This time is described in the Reselection Counter (RC). This counter is randomly selected from a given interval of values that vary depending on the RRI:

- [5, 15] if RRI ≥ 100 ms (between 1 pps and 10 pps).
- [10, 30] if RRI = 50 ms, then 20 pps.
- [25, 75] if RRI = 20 ms, then 50 pps.

Then, the vehicle can use the granted resources while RC does not reach 0. Every time a transmission is performed using these resources the RC counter is decremented by one. When the RC counter hits zero, with probability P (P may take values from 0 to 0.8), the vehicle will keep the previous resources.

When higher packet transmission frequencies such as 20 or 50 pps are selected, the interval for populating L_3 change to [*SF* – 20 ms ; *SF* + 20 ms] and [*SF* – 50 ms ; *SF* + 50 ms] respectively. In addition, the maximum latency that defines the selection window is 50 ms for 20 pps and 20 ms for 50 pps.

2.3.2. Congestion Control Mechanisms

In some scenarios with a high density of cars or a high data traffic load, it may be necessary to implement some congestion control mechanisms to improve the overall performance. This is why LTE-V Release 14 supports congestion control when operating in mode 4. However, the standard does not specify a specific congestion control mechanism but it provides two different metrics related with the congestion and possible mechanisms to reduce the congestion.

The first metric is known as Channel Busy Ratio (CBR) and provides an estimation of the level of channel congestion. The CBR is estimated every time that a vehicle transmits (or retransmits) a given packet. Consider *n* as the subframe where the transmission it is going to occur. To estimate the CBR, the amount of subchannels in the range [n to n-100] where it was observed an average RSSI higher than a pre-configured threshold. The second metric is the Channel occupancy Ratio (CR) and it provides an estimation of the channel occupancy generated by the transmitting vehicle. The CR is computed as the amount of subchannels used by the transmitting vehicle during a period of 1000 subframes. These subframes can be distributed between past or future subframes and it is up to each vehicle. However it must contain at least 500 past subframes and the future subframes must be already reserved by the transmitting vehicle to be computed in the CR.

The LTE-V standard indicates that a maximum of 16 CBR intervals can be defined. Each CBR interval, has a CR_{LIMIT} value associated. The higher is the CBR the smaller is the CR_{LIMIT} value. For a given CBR level the vehicle should not overpass the CR_{LIMIT} value, if it does so, a congestion control mechanism should be applied. An example of a table with 10 CBR intervals for a transmission frequency of 10 pps can be found in [5]. A very simple process is defined by using these two metrics and the aforementioned table. When a vehicle wants to transmit a packet, or the redundant version of it, it measures the CBR and quantifies its CR. For the measured CBR it looks for the interval where is located and the associated CR_{LIMIT}. If $CR > CR_{LIMIT}$, then the vehicle must reduce its CR below CR_{LIMIT}. To achieve this, the standard proposes some possible mechanisms that can be used indistinctly up to each vehicle.

- **Number of transmissions per packets:** Reduce the CR by avoiding redundant transmissions.
- **Transmission power:** Reducing the transmission power reduces the CBR. If CBR drops to a lower interval, the CR_{LIMIT} increases.
- **Packet dropping:** Reduction of the CR by not transmitting certain packets generated by the application.
- **MCS:** If the transmission occupies more than one subchannel, augmenting the MCS may result in lower subchannels used for transmission and therefore a CR reduction.

During the simulation phase of this thesis, the packet dropping mechanism will be studied. However, the rest of aforementioned mechanisms although will not be implemented and simulated, their impact will be assessed in the studies that will vary the transmission rate, transmission power and MCS. As a consequence, even though the implementation of these congestion control mechanisms will not be implicitly tested, the effect that may cause on the network's performance will be analyzed. As for the packet dropping mechanism, further details are given in the following section

2.3.2.1. Packet Dropping

At the simulation phase of this thesis, the congestion control mechanism to be analyzed is packet dropping. As aforementioned, it consists in not transmitting some packets to reduce the CR below the CR_{LIMIT} associated to the current CBR experienced by the vehicle. It is worth to mention, that dropping certain packets imply losing information that may be relevant or even critical. As a consequence, packet dropping should only be a congestion control mechanism candidate to a real implementation just in case that the information that it is being transmitted is somehow redundant or losing a packet it is not critical for the correct behaviour of the application. This could be the case of messages that contain information of presence, position and basic status of vehicles in the same road. With these types of messages, the fact that a packet is lost, only affects to the periodicity of the information (i.e. transmission rate) but there is no information loss since the next packet will be received. Packet dropping should never be applied to applications that intend to inform of an immediate collision with another vehicle or a pedestrian.

The first step before performing simulations where the packet dropping mechanism is enabled, is to understand how dropping a packet influences the network, specifically the sensing-based SPS. When a vehicle sends the SCI+TB, the sidelink control information contains the reservation for the next transmission. When the vehicle decides to drop the packet there are two approaches. The first one is to send the SCI and the second one to not send it [6]. This is relevant since there is a parameter called "reselect after", that sets the maximum number of missed transmissions (i.e. missed or dropped) before the vehicle is forced to select new resources. Regardless of whether the SCI is transmitted or not, the resource where the vehicle drops the packet is not going to be used nor selected by any vehicle, since when selecting new resources it will see that this CSR will be used. The problems appear in the transmission immediately after the dropped packet as shown in **Figure 4.7**. If the vehicle resumes the transmission using the same resources (i.e. the "reselect after" parameter is set higher than 1) and does not transmit the SCI associated to the dropped packet, the other vehicles may have selected the same resource and potential collision will occur. This approach where the packet dropping mechanism is implemented without sending the SCI associated is discussed in [6]. This approach revealed a very bad performance since dropping the packet causes the resource to be sensed free and thus available for use by the surrounding vehicles leading to collisions. During this thesis, the approach of sending the SCI associated to the dropped packet will be adopted. This approach seems logical because if the SCI is not sent, the granted resources are not correctly managed.

In a nutshell, the operation of the adopted packet dropping approach in this thesis takes into account the "reselect after" parameter works as follows. If the vehicle has configured the "reselect after" parameter to one, when the packet is dropped, the associated SCI will be sent informing that the granted resources will not be used. By this approach, no further reservation will be done and the vehicle will select new resources, making available the previous granted resources. If the vehicle considers a "reselect after" parameter equal to

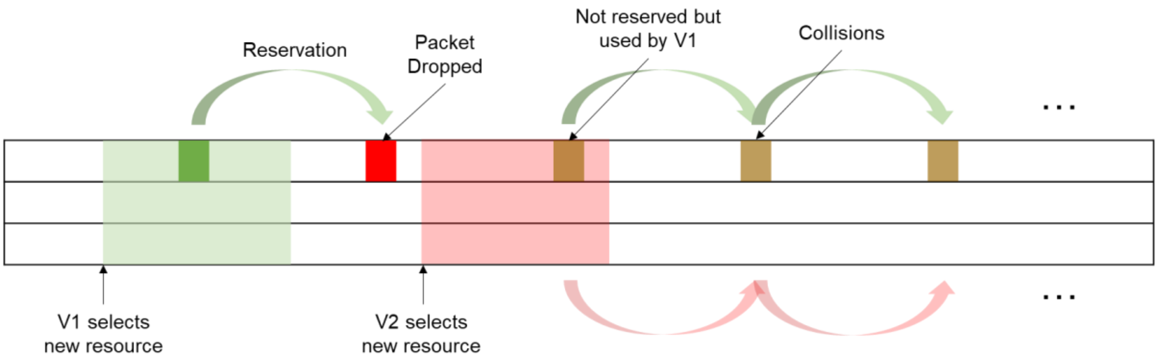

Figure 2.7 Collisions due to Packet Dropping

two, the first dropped transmission will include the SCI saying it will maintain the grant, however another dropped transmission will force the relinquishing of the granted resources. The same applies for "reselect after" values higher than two. Regardless of the value of the "reselect after" parameter, it becomes clear that when the last dropped packet forces the vehicle to select new resources the situation is the same one as having selected a value of one.

2.4. LTE-V Enhancements (V2X Phase 2)

The later releases of the 3GPP specifically the Release 15 [7] introduces the concept of V2X phase 2 also known as eV2X which is intended to cover advanced V2X use cases by enhancing some features of the LTE-V standard. These advanced use cases are more focused on autonomous driving and include platooning, remote driving or sensor and map sharing among others. What is clear is that the requirements to fulfill these use cases are very demanding and could not be covered with initial approach of LTE-V, some of them even will need of 5G technology to be covered [8]. The aforementioned applications may require from a transmission up to 50 pps, maximum latencies between 3 and 10 ms and up to a reliability of 99.99% in terms of Packet Delivery Ratio (PDR). The enhancements mentioned in [7] are:

- **Support for Carrier Aggregation (CA) in mode 4:** CA was available for mode 3 in Release 14. Now it is specified for mode 4 where the sensing-based SPS is extended to support multi-carrier transmission.
- **Support for 64 QAM:** New TB size and TB scaling were incorporated to support 64 QAM. Puncturing was substituted by rate matching.
- **Time reduction at physical layer:** Reduction of the maximum time between packet arrival at physical layer and resource selected for transmission. The value is now 10 ms (against the 20 ms of LTE-V Release 14).
- **Resource sharing:** Radio resource pool sharing between mode 3 and mode 4 UEs.
- **Transmit diversity:** Specifically the small delay cyclic delay diversity.

3. C-V2X Mode 4 Simulator

3.1. Software

The analysis of C-V2X Mode 4 is performed using a simulator which in fact, it is the union of different software, frameworks and projects that all together allow to create a testing environment of the technology **(Figure 3.1)**.

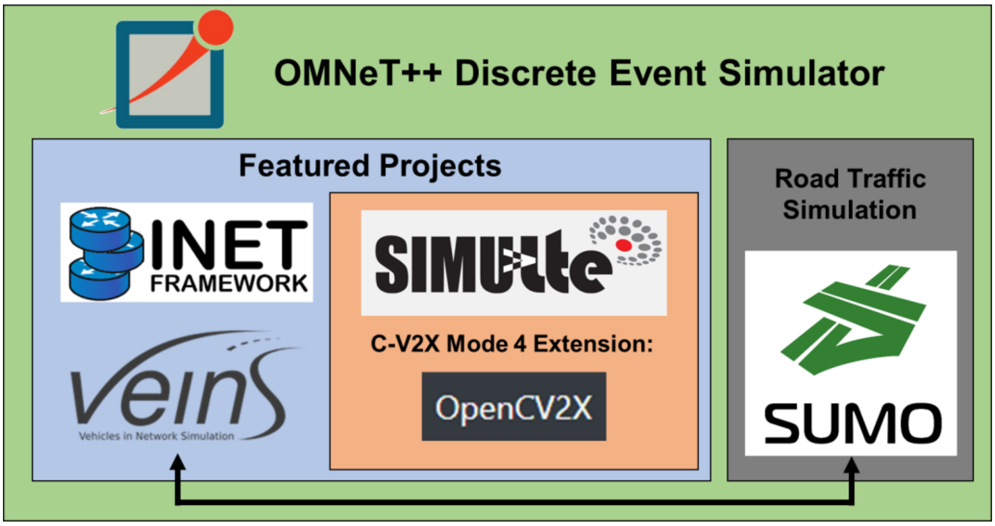

Figure 3.1 Simulation Environment

The core element is Veins [9], which is an open source vehicular network simulation framework that includes a suite of simulation models for vehicular networking. It also takes care of setting up, running and monitoring the simulation. The simulation models are executed by OMNeT++ [10], an event-based simulator while interacting with SUMO (Simulation of Urban Mobility) [11], a road traffic simulator. Then, when a simulation is executed, simultaneously, both OMNeT++ (network simulation) and SUMO (road traffic simulation) work in parallel connected via a TCP socket using the Traffic Control Interface (TraCI) protocol. In a nutshell, when a vehicle is being moved in SUMO, the same movement is reflected in the OMNeT++ simulation as node movements.

OMNeT++ has some featured projects that may be needed to run some simulations. In our simulator, we need to incorporate INET Framework [12]. This framework is an open-source model library for OMNeT++. It provides models for the Internet stack, wired and wireless layer protocols, support for mobility, etc. In addition, an extra framework is needed in our case which is SimuLTE [13]. It is a simulation tool that enables complex system-level evaluation of LTE and LTE Advanced (3GPP Release 8 and beyond). In fact SimuLTE is built on the INET Framework, this is the reason why it was needed it.

We have all the ingredients needed to run an LTE simulation. However, SimuLTE does not provide support for C-V2X. This is where the last and most important element appears. OpenCV2X Mode 4 [14] is an open source implementation of C-V2X Mode 4 (it implements the features of 3GPP Release 14). It is an extension of SimuLTE which integrates with Veins to provide all the C-V2X Mode 4 functionalities.

When it comes to the overall implementation of the different aforementioned elements, the versions of some frameworks must be chosen carefully to provide proper operation of OpenCV2X Mode 4 framework. The documentation with the requirements for the proper operation can be found in [14]. These are the versions that have been used for this thesis: Ubuntu 18.04 as operating system, OMNeT++ 5.6.1, Veins 5.0, SUMO 1.6, INET v3.6.6 and OpenCV2X Mode 4 v1.2.0 (which already includes SimuLTE).

The analysis of the output simulation files with the relevant data could have been performed with OMNeT++. However, since the simulation files are very large OMNeT++ is overgrown very fast. Instead of that, with help of OMNeT++, CSV files prepared to be used with Python were created with the relevant data to be analyzed. All the important analysis and plots are performed with help of Python scripts that I have created. Pandas library has been used to manage the big data files and transform them into easy manageable data frames. With help of Matplotlib library the required plots have been created from the Pandas data frames.

3.2. Simulation Environment

The previous section was a short summary of the different pieces that build up the final C-V2X Mode 4 simulator. This section is intended to understand how the simulation environment is built and how it works.

Everything starts with the installation of OMNeT++ Integrated Development Environment (IDE) which is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. The first step then was to get acquainted with OMNeT++ IDE since I have never worked with network simulators. To do so, I have followed the *TicToc* tutorial [15]. This tutorial is a guide through building and working with an example simulation model that at the same time show some of the commonly used OMNeT++ features. Even though this example has nothing to do with vehicular networks and I was not going to program or design any network from scratch, it was necessary to learn very important things that I was going to need later.

OMNeT++ is based on modules that communicate between them by exchanging messages and written in C++ and using the simulation class library. These active modules are usually referred as simple modules. A simple module can be grouped into compound models and so on, there is no limit of grouping levels **(Figure 3.2)**.

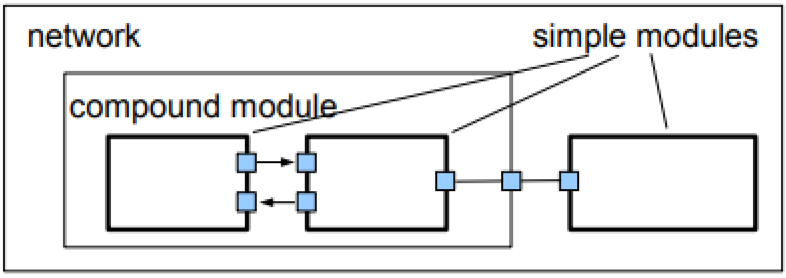

Figure 3.2 Model Structure in OMNeT++ [16]

Either simple or compound modules are connected between them by gates. As it has been mentioned, modules communicate between them by exchanging messages that a part from the typical timestamp, can be customized to contain arbitrary data. Simple modules, exchange messages typically via gates, however, it exists the possibility of sending directly the messages to the destination module. Gates are the input and output interfaces of a module. Therefore, when sending a message, the destination module will receive the message through its input gate whereas the sending node will send the message through its output gate. The link between input and output gates is known as a connection.

Connections can be only defined with one level of hierarchy that refers to connections between compound modules, submodules inside a compound module or a connection between a gate of one submodule and a gate of the compound module. Due to that fact, usually messages are intended to be generated and sent by simple modules and be received by simple modules too. Finally, modules may contain parameters that can be used to pass configuration data to simple modules and to define the model topology. These parameters may take string, numeric or Boolean values. Since the parameters are represented as objects in OMNeT++ they can not only hold constant values but also generate random values, interact with the user to ask for the value and even hold expressions referring to other parameters.

The modules and their connections (the structure of the model) are defined by the user by using the NEtwork Description (NED) language. A NED file usually contains:

- **Simple module declarations**: Describe the interface of the module: gates and parameters.
- **Compound module definition**: Declaration of the module's external interface (i.e. gates and parameters), and the definition of submodules and their interconnection.
- **Network definition**: Compound modules that qualify as self-contained simulation models.

Now that the module structure has been explained, the specific modules that are used for the C-V2X Mode 4 can be explained. The main modules that are going to be described are those that are associated with the vehicle design, which mainly implies the Open Systems Interconnection (OSI) layers description. The NED files and their associated C++ files (they define the behaviour of the simple module) that are going to be explained from now, can be found at the *src/* folder of the OpenCV2X Mode 4 v1.2.0 project. It is important to take into account that OpenCV2X Mode 4 project is just an extension of SimuLTE and therefore there are several modules related with LTE functionalities that are defined but not used in our simulations.

The main element is the car, which is represented as a node in OMNeT++. The car type is called *CarNonIp* **(Figure 3.3)** and it has three different submodules.

- **mobility:** refers to the mobility and basically is in charge of how the mobility of the car and its connection to SUMO is managed.
- **appl:** This submodule represents the application layer. It has a connection with the *lteNic* compound module.
- **lteNic**: This submodule is a compound module that represents the Network Interface Card (NIC) of the vehicle. The NIC has a connection with the *appl* module as well as with the radio interface.

There is something that should be also mentioned. When defining a submodule of a certain compound module or network such as the three aforementioned ones, the submodule can be specifically written in the same NED file, reference to another NED file or even reference to a wide range of NED files. When a compound module is being designed it is possible that the specific file intended to provide this submodule functionality is not defined and/or decided. A very clear examples are the three aforementioned modules. A general car has been defined, however by generating different application layer submodules, we can

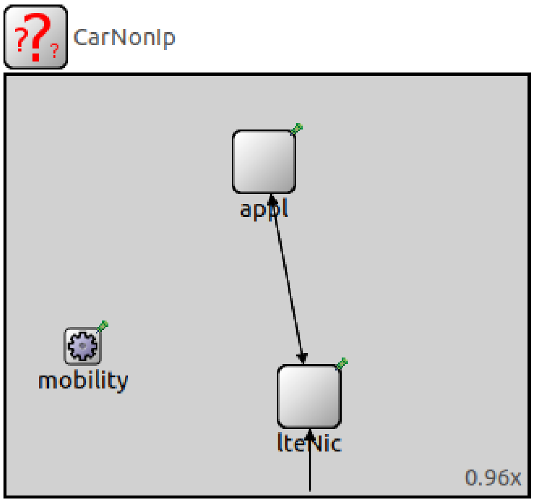

Figure 3.3 CarNonIp.ned (Design View)

decide at the moment of configuring the final simulation, which is the application layer behaviour we want to give to the car. This is done by passing the name of the NED file as a parameter to the compound module. The same applies for *mobility* and *lteNic* submodules. This is the typical way of designing compound modules and applies to the following modules unless otherwise indicated. From now on and considering what has been mentioned in the previous paragraph, the main modules that are relevant for the C-V2X Mode 4 algorithm are going to be explained.

Let's start by the application layer (*appl*) that is represented by the *mode4App.ned*. This module as mentioned previously is in charge of implementing the application layer of the car. In that case the configurable parameters are the size of the packet that it is going to be broadcasted, the packet generation rate represented as the time between two packets are generated and the priority of the packets among others.

Before talking about the NIC is worth to mention, that inside a NED file, several modules can be defined and they do not have to be connected between them necessarily. This is the case of the *LteNic.ned* file which contain several compound modules that represent different types of NIC (e.g. for eNB, relays, standard devices …). In our case, the important NIC and the one that has to be used is represented by the *LteNicVUeMode4* module **(Figure 3.4)** inside the *LteNic.ned* file. As it can be observed, this compound module contains inside four different modules that are associated with four different layers. The top one is represents the PDCP/RRC. This module is connected to the output gate of the NIC which at the same time and as it can be observed in **Figure 3.3**. The module in charge of implementing these functionalities is named *LtePdcpRrcUeD2D* and it can be found at the *LtePdcpRrc.ned* file. The second one is referred as *rlc* and as its name indicates, it is in charge of implementing the RLC protocol. The module is named *LteRlc* and it is described in the *LteRlc.ned* file. It is connected with the upper PDCP/RRC layer and the bottom MAC layer. For the sake of simplicity, these two last modules will not be analysed in depth, for further information just have a look at the mentioned files. The next layer which it is connected with the RLC layer and the physical layer is the MAC layer. This module is named *LteMacVUeMode4* and it is described in the *LteMac.ned* file. This module contains parameters that are used to configure different characteristics such as subchannelization scheme, MCS, maximum latency, RRI or enable/disable congestion control mechanisms.

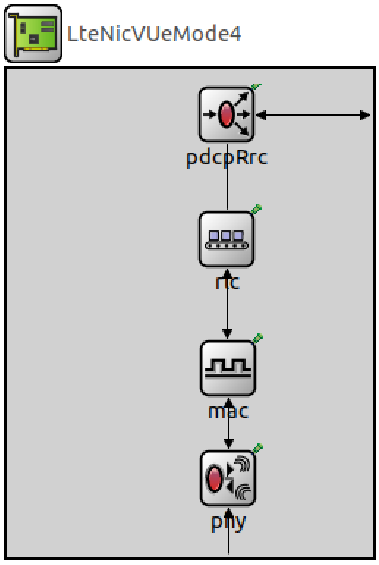

Figure 3.4 LteNicVUeMode4 Module (LteNic.ned – Design View)

Finally, the last layer named *phy* represents the physical layer which is connected to the MAC layer and has a connection to outside the NIC. This connection is the one that goes out the NIC and as it has been mentioned is connected with the radio medium at the same time. The module it is named *LtePhyVueMode4* and it is described in the *LtePhy.ned* file. It manages parameters such as the subchannelization and threshold RSSI. In **Figure 3.5** a summary of the car structure and that the different modules that make it up is available.

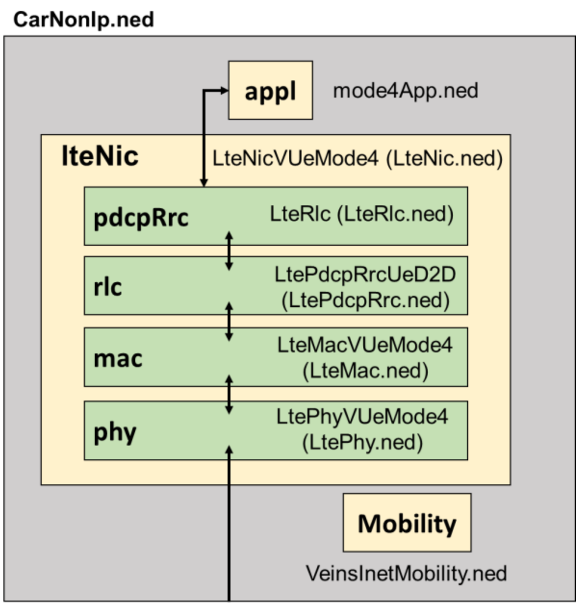

Figure 3.5 Vehicle Structure (NED files)

At the section where the module parameters and its functionality were described, it has been said that can be used to pass configuration data to simple modules. These simple modules have an associated C++ file where the functionality is implemented. Let's say then that the NED files are the description of how the network is built and the C++ files describe the behaviour of the simple modules. For example, the *LteMacVUeMode4* module has an associated *LteMacVUeMode4.cc/h* file where the sensing-based SPS algorithm and the congestion control mechanisms among other features are implemented. Therefore, those parameters must be defined somewhere by the user, if not, the default value defined in the NED file will be taken (if any default value has been defined, if this is not the case, the user will be asked to introduce a value manually when the simulation is launched). This type of file has the extension *.ini* and usually is named as *omnetpp.ini*. It contains the main parameters that describe the behaviour of the C-V2X Mode 4 physical and MAC layer, the sidelink configuration, the sensing-based SPS, the scenario (and its location inside the project tree) that must be used and some other simulation related parameters that are defined in the NED files. This file, may contain different configurations. When the simulation is launched from this file, the user can select which configuration wants to use. Thanks to that, different values for the same parameter can be separated into different configurations for sake of simplicity at the time of starting a simulation.

3.2.1. Simulation Operation

This section intends to explain what a simulation consists of. The first action that we have to perform before starting the simulation, is to connect OMNeT++ and SUMO via a TCP socket using the TraCI protocol. To do so, we have to use the terminal and go to the root folder of the Veins project. There, we will find a python script called *"sumo-launchd.py"* that must be executed with the following command *"-vv –c /usr/bin/sumo"* where the specified route after the *–c* instruction points to the SUMO launcher file. Once this is done we will see how the script starts listening for the TCP connection **(Figure 3.6)**.

```
dalego1997@dalego1997-VirtualBox:~/src/veins-5.0/veins-veins-5.0$ ./sumo-launchd.py
 -vv -c /usr/bin/sumo
Logging to /tmp/sumo-launchd.log
Listening on port 9999
```

Figure 3.6 OMNeT++ - SUMO connection via TCP

Now we can go back to the OMNeT++ IDE. After setting up the *omnetpp.ini* file and choosing the desired configuration, we can start the simulation. OMNeT++ offer two different user interfaces to execute a simulation, in graphical interface (known as *Qtenv*) or the console or command line interface (known as *Cmdenv)*. In all my simulations I have run the simulations in console mode since the graphical mode has a very high graphical output that *Cmdenv* does not have. Due to that fact, the command line environment is much faster. In addition, *Cmdenv* offer progress feedback such as elapsed time, simulation time, progression percentage.

Now we can run the selected configuration with *Cmdenv* selected and automatically it will throw a command to start the simulation. The first that will do is try to connect to SUMO using the TraCI protocol via TCP. As we have started the python script, it will finally connect and start the SUMO simulation scenario that has been defined in the *omnetpp.ini* file and designed with SUMO. The scenarios that are created for this thesis are described in **Section 3.3** but basically consist in highways with different traffic densities. At the beginning of the SUMO simulation, the cars are deployed from both ends and begin to circulate with the conditions that were defined in the SUMO simulation files. Due to the fact that the cars start appearing at the ends of the defined highway, there is a transitory time until all the cars are deployed and the simulation stabilizes. The idea then is let the SUMO simulation run until the transitory part has finished and then start with the OMNeT++ simulation. There is a parameter that must be set in the *omnetpp.ini* file that controls when the OMNeT++ simulation must start. When this point in time is reached, all the vehicles that are deployed in the SUMO simulation, are registered as nodes (specifically and as mentioned in the previous section, each car is “loaded” with a full OSI stack), the different layers are initialized and the vehicle mobility represented as a node in OMNeT++ is controlled by TraCI.

From this point, the simulation will continue as programmed in the application layer of each vehicle. Immediately after the car is deployed, the first packet transmission is scheduled with a delay that can range from 0 to 1 second with ms precision. This only happens with the first packet and it is a solution adopted to avoid that all the vehicles send their first packet at the same time. Once the scheduled time is reached, the application layer generates an alert packet with the length that has been defined in the *omnetpp.ini* file with broadcast destination for all the vehicles that are in the simulation. It also marks a timestamp to be later used as a reference of the time between the packet generation and reception at the other vehicle. To do so, the packet is sent to lower layers. In addition, a new alert packet generation and transmission is scheduled after a certain period of time known as transmission periodicity and defined also in the *omnetpp.ini* file. In the MAC layer, procedures such as the sensing-based SPS and the generation of the scheduling grant in case there is no granted resources are performed. The packet then is sent to the physical layer where the SCI and TB are prepared and broadcasted as air frames using the granted resources by the MAC layer. The physical layer is also in charge of computing the CSRs or decoding the air frames from other vehicles. All vehicles in the simulation will receive this air frame and will try to decode it. However, in real life there would be some cars that would not receive the packet by different reasons. This is why the physical layer will analyze the air frame (note that the air frame may be either SCI or TB) and it will check if under the current conditions such as Signal to Noise Ratio (SNR), Signal to Interference and Noise Ratio (SINR) or packet sensing ratio the air frame could have been correctly decoded in real life. An accurate description of the possible errors that may appear when transmitting a packet is given in **Section 3.2.4**. When the TB and its associated SCI are correctly decoded at reception, the alert packet which has been generated in the application layer of the transmitting vehicle is time stamped again and the difference between the generation and reception time is calculated as the delay to transmit this packet.

This is how the simulation works. Until the end of the simulation which is defined in the configuration file the vehicles will broadcast and receive alert packets. Furthermore, the vehicles calculate update periodically every 100 ms the CBR. This information can be used for congestion control mechanisms if enabled. Once the end of the simulation is reached, the nodes are unregistered and the final statistics are saved in *.sca* and *.vec* files for scalar and vector statistics respectively.

3.2.2. Parameters

The intention of this subsection is to map the names that some of the parameters have inside the simulation, with their function within the scope of C-V2X Mode 4. This will be relevant since in the following sections some characteristics of the C-V2X Mode 4 will be referred directly as its name in the simulator.

- ***packetSize***: Sets the size of the packet in Bytes.
- ***period***: Determines the period of packet transmission in each vehicle. Instead of defining it in terms of pps or Hz it is directly set in seconds between each transmission.

- ***RRI***: Determines the resource reservation interval for each vehicle. It essentially implies that a car will have the assigned resource available to transmit every amount of time that the RRI indicates (i.e. if subframe N is selected for transmission, the packet will be transmitted in the Nth subframe and the following transmissions will occur in N + RRI, N + 2*RRI…). The RRI usually is set equal as the transmission rate. In the simulator it may take values such as 0.2, 0.5, 1, 2…10. To get the RRI this value must be multiplied by 100 ms.
- ***subchannelSize***: Determines how many RBs/subchannel are allocated. This size includes also the 2 RBs needed to transmit the SCI.
- ***numSubchannels***: Determines in how many subchannels is divided the channel.
- ***adjacencyPSCCHPSSCH***: This parameter is used to set the subchannelization scheme to adjacent PSCCH-PSSCH (i.e. set to true) or non-adjacent PSCCH-PSSCH (i.e. set to false)
- ***MCS***: The MCS is divided in two different parameters, *minMCS-PSSCH* and *maxMCS-PSSCH*. Those parameters, can take values from 0 to 28. With the *maxMCS-PSSCH* the maximum MCS that a vehicle can set to perform a transmission is defined. If it is between 0 and 9, QPSK is selected, from 10 to 16, 16QAM and finally if it is between 17 and 28 the maximum modulation is 64QAM.
- ***[minSubchannel,maxSubchannel]-NumberPSSCH****:* Defines the minimum and maximum number of subchannels that a vehicle may use to transmit.
- ***probResourceKeep***: Determines the probability of a certain vehicle of maintaining the actual granted resources. When the RC reaches 0, the vehicle must select new resources with probability 1 – *probResourceKeep* where *probResourceKeep* may take values from 0 to 0.8.
- ***d2dTxPower***: As the name of the parameter suggests, it defines the transmission power in dBm that the vehicle must use to direct communication between vehicles.
- ***useCBR***: This variable is a Boolean and it is used to configure the cars to use the CBR intervals (if defined) for congestion control purposes. It must be set to true if not the car can't use a congestion control mechanism.
- ***packetDropping****:* If this parameter is set to true (and *useCBR* is also set to true) the packet dropping congestion control mechanism is enabled. If is necessary, the cars will reduce its CR by dropping certain packets generated by the application layer.

This group of parameters will be changed and tuned to different values to check the influence under different scenarios.

3.2.3. Base Configuration

Before starting with the simulations, a base configuration **(Table 3.1)** has been defined which will be not modified across the different simulations. If not mentioned explicitly, only the intended parameter that is going to be analyzed is the one that will be modified.

Table 3.1 Base Configuration Parameters

Parameter	Value
packetSize	190 Bytes
period	0.1 s
RRI	1
subchannelSize	16
numSubchannels	3
adjacencyPSCCHPSSCH	true
Bandwidth	10 MHz
Carrier Frequency	5.91 GHz
MCS	7
[minSubchannel,maxSubchannel]-NumberPSSCH	[1,1]
probResourceKeep	0.4
d2dTxPower	23 dBm
useCBR	false
packetDropping	false
reselectAfter	1
RSRP Threshold	-128 dBm
RSSI Threshold	-92 dBm

The simulation duration has been selected to last 512 in all the studied cases. The first 500 seconds, are always used to achieve the stationary part of the SUMO simulation. It is a prudent time for all the cars to be introduced in the simulation and overcome the transitional part. From this point, the C-V2X Mode 4 standard is enabled and the different vehicles inside the simulation start sending broadcast packets to the rest of vehicles during 12 seconds, when the simulation finishes. This value was selected by default at the simulator and it has been checked that it is a prudent time to get insightful results and moderate simulation times. During these 12 seconds, the vehicles broadcast a packet every 100 ms, thus a frequency of 10 pps during. In accordance with this transmission rate of 10 pps, the RRI is set to 100 ms. The size of the packet is 190 B which a typical size for short messages in vehicular communications. The channel is configured to work at a frequency of 5.91 GHz with a bandwidth of 10 MHz. In addition is divided into 3 subchannels with 16 RBs per subchannel resulting in a total of 48 RBs. Even though the standard make it possible for vehicles to transmit using more than one channel, it has been decided to limit to just one channel the number of channels that a vehicle can use. All vehicles will use MCS Index 7 which corresponds to a QPSK (i.e. modulation order 2) to transmit their packets. The modulation and Transport Block Size (TBS) index that corresponds with an MCS Index 7 is TBS Index 7 (see table 7.1.7.1.1 in [17]). Then, it is necessary to have a look at the transport block size table 7.1.7.2.1-1 in [17] where the maximum number of bits that fit in a single TB is delimited by the TBS Index and the number of RBs necessary to transmit this TB. Note that in **Table 3.2** a section of the aforementioned table with the required data is represented. Since the packet size used in this application is 190 B (i.e. 1520 bits) the packet fits in 13 RBs. This is calculated by searching which is the minimum number of RBs necessary to fit the packet in a single TB for a given TBS Index (i.e. with TBS Index 7 and 13 RBs the TBS is 1608 bits and then, 190 B fit in a single TB). Considering that the sidelink has been configured with subchannels of 16 RBs and the first two are used for SCI transmission, the inefficiency is almost inexistent since just 1 RB is not used in the transmission. The subchannelization scheme is adjacent PSCCH + PSSCH. The resources that have been assigned to the vehicle will be kept with a probability of 0.4 when the reselection counter reaches zero. In addition, the vehicle cannot retransmit a packet if it has been lost. The transmission power of the vehicle is 23 dBm and the RSSI threshold is set to -92 dBm and the RSRP threshold is set to -128 dBm. As it has been defined in the standard, the CBR and CR_{LIMIT} can be used to reduce the congestion in some networks. To do so, the simulator takes profit of an example of CBR intervals and CR_{LIMIT} from 3GPP working documents which can be found in [5] **(Table 3.3)**. By default there is no congestion control mechanism implemented in the simulation unless it is mentioned.

Table 3.2 Section of Transport Block Size Table 7.1.7.2.1-1 in [17]

I_{TBS}	Number of Resource Blocks										
	…	7	8	9	10	11	12	13	14	15	…
…											
5	…	600	680	776	872	968	1032	1128	1224	1320	…
6		712	808	936	1032	1128	1224	1352	1480	1544	
7		840	968	1096	1224	1320	1480	1608	1672	1800	
8		968	1096	1256	1384	1544	1672	1800	1928	2088	
9		1096	1256	1416	1544	1736	1864	2024	2216	2344	
…											

Table 3.3 CBR intervals and CR_{LIMIT} for congestion control

CBR Measured	CR_{LIMIT} (10^{-3})
CBR ≤ 0.65	No limit
0.65 < CBR ≤ 0.675	1.6
0.675 < CBR ≤ 0.7	1.5
0.7 < CBR ≤ 0.725	1.4
0.725 < CBR ≤ 0.75	1.3
0.75 < CBR ≤ 0.775	1.2
0.8 < CBR ≤ 0.825	1.1
0.825 < CBR ≤ 0.85	1.1
0.85 < CBR ≤ 0.875	1.0
0.875 < CBR	0.8

3.2.4. Statistics Collection

When a simulation is performed, there is a process of statistics collection which is already coded inside the simulation. These statistics have two different forms, either scalars or vectors. Both types are stored in data files (.sca and .vec respectively) that can be analyzed with help of OMNeT++. Instead of performing an analysis with OMNeT++ which by my experience is slower and sometimes hard to manage, the analysis is done with some Python libraries. The data files that are stored from the simulation, can't be read with no pre-processing by Pandas library. All the scalar data is converted by means of OMNeT++ into a .csv file which is ready to be read and easily transformed to a table using Pandas. A similar procedure is followed with the vector file, but in that case instead of generating a unique .csv file with all the vectors, a pre-selection of the desired ones is performed and a different .csv file is created for each of the iterations over the variable of interest.

One of the main concerns when analyzing the simulations and interpreting the collected statistics will be the PDR, which is a metric that help to understand very fast which is the overall performance of the network. It mainly describes how many transmitted packets, thus TBs, where correctly received as a percentage of the total transmitted TBs by all the vehicles in the network. The rest of TBs for obvious reasons suffered from a transmission error. Those errors are analyzed per single SCI+TB transmission and can be classified in four different types if we decide to focus on the TB reception:

- **Half-Duplex:** The C-V2X radio is half-duplex. This type of error is caused because the receiving vehicle is transmitting its own packet at the same subframe where it was supposed to receive the SCI+TB. Two vehicles have a certain probability of selecting the same subframe to transmit their packet and therefore not receiving a SCI and the associated TB due to half-duplex. This probability does not depend on the distance between both cars, the channel occupancy or the SPS scheme. This quantity can be defined as the ratio between the number of pps that each vehicle transmits and the number of subframes within a second (i.e. 1000 subframes).

- **Collision/Interference:** In that case, the reception of a TB fails because it has not been received with enough SINR to be correctly decoded. It considers all the cases where the TB reception fails because the result of the interference and/or collisions from other vehicles that are transmitting their packet in the same resource (i.e. subframe and subchannel). In that case, it depends on the SPS configuration, transmission parameters, distance between transmitter and receiver and traffic density.
- **No SCI:** It has been mentioned previously in this thesis, that for the correct reception of the TB it is necessary to decode correctly the associated SCI. When the cause of not receiving a TB it is that the associated SCI has not been correctly decoded the error is classified inside that block. We can translate the no SCI result by combining some results so we get the true outcome for the TB (i.e. while it was lost for not having an SCI why was the SCI itself lost through unsensed, propagation or interference reasons). Then, the errors associated with the correct reception of the SCI associated to the TB can be divided in:
    - **Unsensed:** This error is caused when the SCI is received with a signal power below the sensing power threshold and it can't be decoded. This error mainly depends on the transmission power, the sensing power threshold, the propagation and the distance between transmitter and receiver. This error is defined by the well-known formula of the probability of receiving a local average power higher (P_r) than the minimum required power (P_s'). The minimum required power P_s' is -90.5 dBm whereas the standard deviation σ that depends on the environment it is set to 3.

$$P(P_r \geq P_s') = \frac{1}{2} + \frac{1}{2}\, erf\left(\frac{P_r - P_s'}{\sqrt{2}\sigma}\right) \qquad \textbf{(3.1)}$$

    - **Collision/Interference:** It is caused by the same reason that has been explained for the TB. The unique difference is that the collision now prevents the SCI from being correctly decoded.

3.3. Simulation Scenarios

In order to collect data under different situations, different scenarios were created with help of SUMO **(Figure 3.7)**. Even each of the scenarios is intended to reproduce a different situation in real life, all of them have some common characteristics which are:

- There are only cars in the simulation.
- The road type is always a two-way highway with three lanes per way. The width of each lane is 4 m.
- Given the length of the highway which depends on the scenario, the number of vehicles is always maintained. The simulation focuses always on the given length of the highway, when a car arrives to the end of the highway it appears again at the beginning of the same lane with the same conditions. In fact it is like focusing on a given segment of a real highway which follow the same car distribution.

- The vehicle has an acceleration capability of 2.6 m/s^2 and a deceleration capability of 4.5 m/s^2. The car will always be deployed in the simulation with the maximum speed.
- The car follow model is the Krauss model developed by Kraußin 1997 and based on the safe speed [18] [19]. The main idea of the original model is let vehicles drive as fast as possible while maintaining perfect safety (always being able to avoid a collision if the leader starts braking within leader and follower maximum deceleration bounds).
- For each of the scenarios, there is a transitory part until the simulation is stabilized. This occur when all the cars for which the simulation is intended, are deployed. For all the scenarios this time is set to 500 seconds.

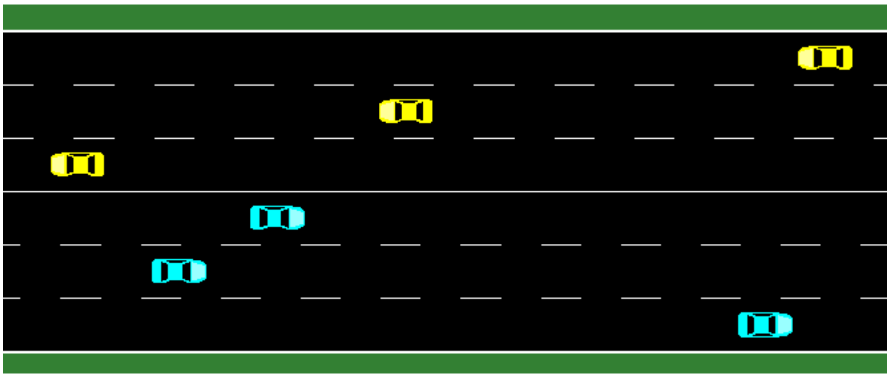

Figure 3.7 Fast Highway Scenario

Now that the general characteristics are described, let's perform a brief explanation of the intention of each simulation scenario. The main characteristics for each of the simulations can be found in **Table 3.4**.

- **Fast Highway:** The main intention of this scenario is to simulate a real highway with a speed limit of 140 km/h where there are always 126 cars placed along 2 km of road. The traffic density is 10.5 cars/km·lane.
- **Congested Highway:** This scenario wants to reproduce the situation of a highway which is suffering from a traffic jam. The speed limit is 90 km/h due to this situation, however the cars are actually going slower, with a speed around 35 km/h and maintaining the inter-vehicle distance of 2.5 m which is the minimum security distance when driving a vehicle. There are always 252 cars placed along 600 m of road with a traffic density of 70 cars/km·lane.
- **Minor Road:** The minor road scenario, wants to reproduce exactly the same traffic conditions as mentioned in the fast highway scenario, but with a lower speed limit of 70 km/h. The main intention of this scenario is to check in some specific sections of the performance analysis which is the impact of reducing the speed but keeping the traffic conditions.

Table 3.4 Simulation Scenarios Characteristics

Simulation Scenario	Fast Highway	Congested Highway	Minor Road
Highway Length (km)	2	0.6	2
Max. Speed (km/h)	140	90	70
Number of Cars	126	252	126
Cars Density (cars/km·lane)	10.5	70	10.5
Minimum Gap between Cars (m)	50	2.5	50

3.4. Limitations

During the development of this thesis, I have been in contact with the developer of the main files needed to implement the Mode 4 capability on the SimuLTE package. During these conversations some questions with respect to different capabilities of the LTE-V Mode 4 and the implementation of them to the simulator raised. The first release of these files was presented in September 2019, thus some extra corrections were needed during these last months while I was developing the thesis.

- A patch that was not a release itself developed the first week of June, was needed to achieve the correct implementation of the transmission rates of 20 and 50 pps.
- A small bug in the code that I have found at the last week of June, ended with another patch and the repetition of all the simulations that I had performed. The application was not correctly selecting the appropriate MCS among the defined range of selectable MCS indexes given a certain packet size and subchannel configuration. This was causing an incorrect number of RBs to transmit the packet and therefore incorrect results.
- The lack of documentation about some parts of the code has been a handicap, usually resolved by exchanging some emails with the main developer.
- There is a limitation that has not been solved during these months related with the packet segmentation that does not work in the actual implementation. Therefore, the maximum application packet size allowed is the one that fit in a single transmission. This means that the MCS, RBs/subchannel, maximum number of subchannels that a vehicle can use to transmit (i.e. the V2X sidelink configuration) must be adjusted to fit the desired application packet size. If it is not adjusted, the transmission will not occur since the packet cannot be divided to be transmitted in more than one subframe.

- The number of subchannels used to transmit is selected randomly from the specified range with the two parameters that define the minimum and maximum number of subchannels that a vehicle may use to transmit. This produces inefficiency in two ways. On one side, selecting a number of RBs less than the required to transmit the packet, will trigger a drop of the actual granted resources and a new resources selection. On the other side, if the number of granted RBs is higher than the required, the vehicle will have granted resources with more bandwidth than required to perform the transmission which is inefficient. To avoid this problem, in some simulations I had to manually select a fixed value of subchannels that all vehicles must use to transmit. I had to take into account the MCS value, the RBs needed to transmit the TB and the subchannelization scheme, to calculate how many subchannels needs the vehicle to transmit this packet.

4. Performance analysis

With all the simulator configured and all the ideas with respect to C-V2X Mode 4 clear, it is time to perform a deep analysis on the performance of the technology. During the different subsections of this chapter, different key points of the LTE-V will be evaluated considering the different scenarios that have been previously explained **(Table 3.4)**. This includes parameters related with traffic generation such as the transmission frequency, other related with the vehicle configuration such as the transmission power, probability of keeping the granted resources or modulation and coding scheme. In addition, different subchannelization schemes will be analyzed. I will take also profit of the congestion control mechanisms implemented by the simulator such as packet dropping to see if this helps or is a handicap to the original results.

4.1. Transmission Frequency

The first study item of this thesis is related with the transmission frequency measured in how many packets per second a vehicles transmits. As it has been explained in **Section 2.2**, the standard considers transmission rates as low as 1 pps (i.e. the minimum transmission rate) up to 50 pps. To study which is the impact of the transmission frequency, 1, 2, 5, 10, 20 and 50 pps transmission rates were considered under the fast and congested highway scenarios. The rest of configurable parameters take the base configuration values.

The modification of the transmission rate has an impact on the channel congestion. The CBR experienced during the simulation in each car has been calculated and averaged over all the cars in the simulation. In **Figure 4.1** the transmission rate against the average CBR (0% represents no occupancy in the channel and 100% that the channel is fully congested) against the fast and congested highway scenarios. Having a look at the plot and as it is expected, the congested highway scenario has an average CBR higher over all the different transmission rates since there is a higher density of cars. With respect to the effect of the transmission rate to the CBR it is clear that the higher is the transmission rate, the higher is also the average CBR with no exception. This can be explained by the following reasoning. When the transmission rate increases, it is obvious that for a given period of time, the number of transmissions increases. Considering that the CBR is a metric that analyzes the last 100 subframes to check if it measures a RSSI higher than a pre-configured threshold **(Section 2.3.2)**, increasing the transmission rate will increase the number of subframes where the vehicle detects a higher CBR. To understand why the congested scenario has a higher CBR, the high vehicle traffic density has to be taken into account. Not only the higher number of vehicles, and consequently transmitted packets, increase the congestion of the channel, but also the fact that there is a higher vehicle traffic density. The cars are separated by shorter distances and the RSSI they measure will be higher than the one experienced at the fast scenario. All together the higher number of transmitted packets and the density of the traffic contribute to the high average CBR values. In fact, the average CBR experienced for a transmission frequency of 50 pps in the congested scenario is a 99.57% thus the channel is near the total congestion. It would be good to increase the given bandwidth to reduce the CBR in this channel or apply congestion control mechanisms to avoid possible problems when reserving new resources. In case of the fast highway scenario the maximum CBR is measured also with 50 pps and the average measured is an 84.88%.

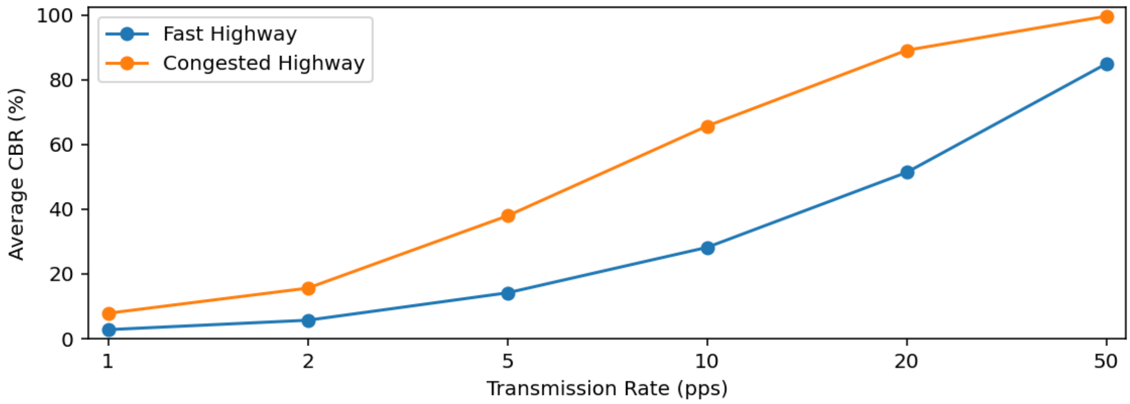

Figure 4.1 Average CBR vs Transmission Rate

The delay is an important metric since receiving a packet after a given amount of time may imply that the information is not relevant anymore. The delay in that case is the time since the packet is generated at the application layer of the vehicle until is received by the application layer of the destination vehicle. In **Figure 4.2** the average of the delays experienced by each packet received is plotted against the transmission rate to analyse which is the impact. Giving a glance to the plot, the first thing that surprises is the fact that increasing the transmission rate reduces the packet delay. In order to understand this, it is necessary to go back to the sensing-based SPS algorithm explanation in **(Section 2.3.1)** specifically to the part where the length of the selection window is mentioned. The duration of the selection window is determined by the application latency constraint. By default for transmission rates equal or smaller than 10 pps the selection window length is 100 ms (unless smaller latency constraint is decided), for 20 and 50 pps the selection window length is 50 and 20 ms respectively. In this simulator the selection window is 100 ms for 1 to 10 pps, 50 ms for 20 pps and 20 ms for 50 pps. Having these things into account it starts to get clearer why we have such an unexpected plot. The selection window is used to identify all the candidate resources that could be granted for the vehicle. The smaller is the selection window the earlier can the resources be scheduled. As a consequence, the first and following transmissions with the same granted resources. Let's consider a scenario where the transmission rate is 20 pps. When the vehicle has to select resources, it considers all the CSR in the selection window of 50 ms. On one hand, there is a certain probability depending on the packet traffic conditions that the CSR is selected at the first subframe and thus the transmission will occur 1 ms after the packet is generated whereas this granted resources are kept. On the other hand, there is also a certain probability that the selected CSR is the last subframe of the selection window and thus the transmissions will occur 50 ms after the packet is scheduled. It is easy to see that on average with a large number of transmissions, the transmission will occur after half of the selection window length. This is the reason why on average, the delay is around 55 ms (including also the average propagation delay) for less than 10 pps, 28 ms for 20 pps and 13 ms for 50 pps. In case that it is desired to reduce the delay for any of the transmission frequencies, the selection window must be reduced to meet the application delay constraint.. For the next sections, it will not be necessary to check the delay since nothing related with the selection window will be changed. Depending on the transmission rate, the average delay will met the aforementioned values.

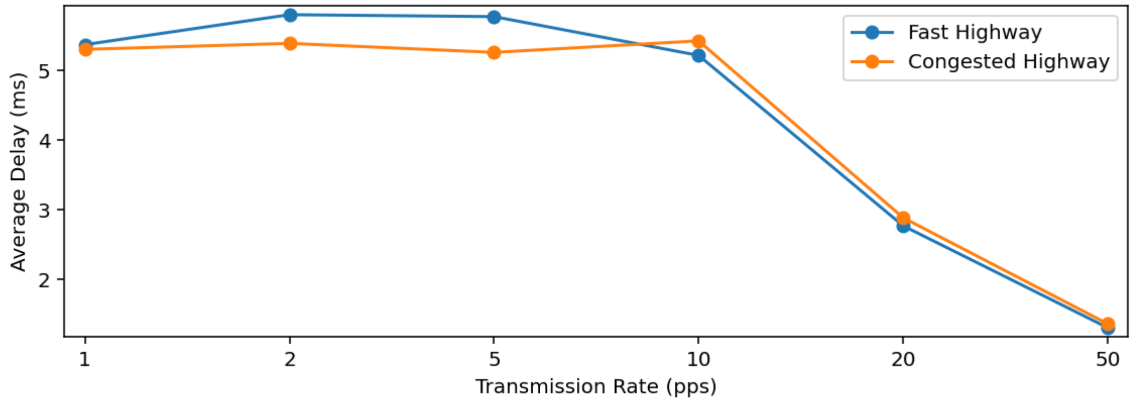

Figure 4.2 Average Delay vs Transmission Rate

One of the most important metrics when analyzing the performance of a network is the PDR. In all the simulations performed for this thesis, the PDR is understood as the number of decoded TBs divided by the total number of received TBs. To analyze which is the impact of the transmission frequency, the PDR has been plotted with respect to the distance that separated the transmitter and receiver car for six different transmission rates. During the PDR analysis, the simulation within the fast highway and congested highway scenarios was separated in two different figures.

Fast Highway Scenario

In **Figure 4.3** the PDR against the distance for the fast highway scenario is shown. In this scenario where we have a low vehicle traffic density we can transmit up to 10 pps and we will have a PDR higher than 90% at transmissions below 400 m. When considering a transmission rate of 20 pps the performance decreases a little bit and finally we can see how with 50 pps the PDR decreases to a 50% at 400 m transmissions requiring of transmitter-receiver distances ≤ 150m.

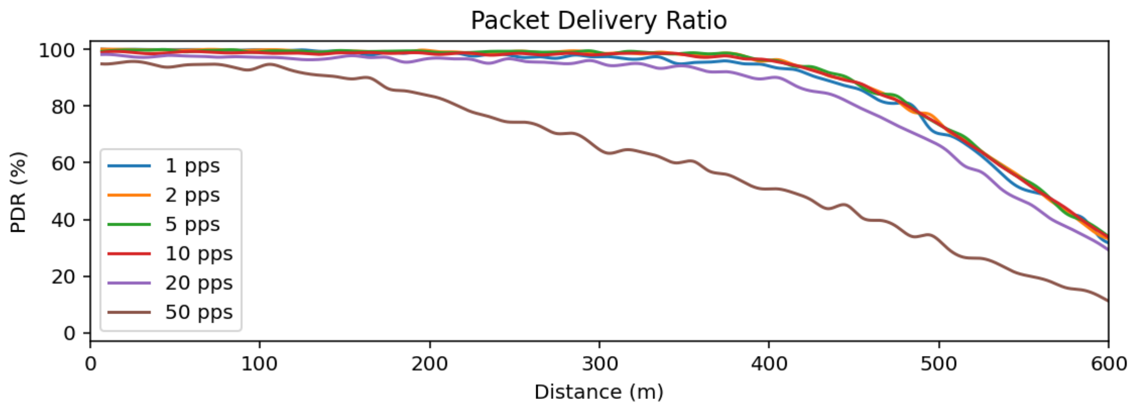

Figure 4.3 PDR vs Distance - Transmission Frequency (Fast Highway Scenario)

The question is which is the cause of such a bad performance at high transmission rates? During **Section 3.2.4** the different transmission errors were introduced. Now it is time to analyse each of the mentioned possibilities to have a picture of which is the real impact of the transmission rate over the PDR. The first type of error that is going to be analysed is the half-duplex type. In **Figure 4.4** the half-duplex fail ratio is plotted against the distance

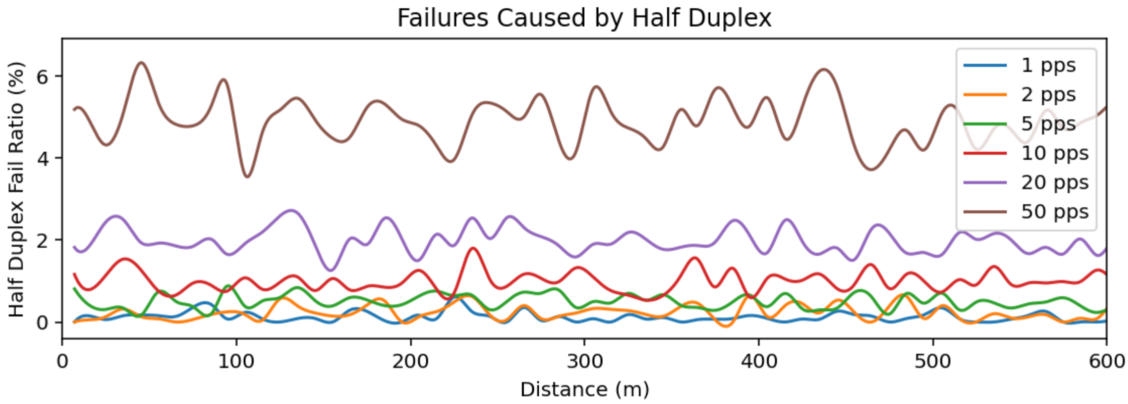

Figure 4.4 Failures Caused by Half-Duplex - Transmission Frequency (Fast Highway Scenario)

and different transmission rates. Taking into account what has been explained in **Section 3.2.4** the average half-duplex fail ratio observed along all the possible distances makes sense. Let's compute which should be the theoretical half-duplex fail ratio for 50 pps. The probability of two vehicles transmitting in the same subframe is the number of transmissions within a second divided by the number of subframes within a second. This is 50/1000 which gives a 5% of failures due to half-duplex. According to the plot, it can be said that on average the simulation revealed a half-duplex fail ratio approximately equal to this 5% value. From the theory it is known that this only depends on the transmission rate, therefore half-duplex errors will be obviated. The error ratio given will correspond to the ratio between the number of transmissions within a second divided by the number of subframes within a second.

The following reason why a packet may have not been correctly decoded is related with the interference and/or collisions from other vehicles that are transmitting their packet in the same resource. The received SINR as a consequence is not high enough to correctly decode the packet. In **Figure 4.5** the interference fail ratio is plotted against the transmitter-receiver distance. The number of TBs that could not be received caused by interference or collision with another vehicle increases as the number of transmitted packets per second does so. In addition this effect becomes relevant at a certain distance higher than 100 m for 50 pps and 300 m for 20 pps. This effect can be explained by the sensing-based SPS algorithm. When a vehicle has to define the L_1 list of CSRs with at least a 20% of the initial resources it has to consider just CSRs where the PSSCH RSRP measurement is smaller than a given threshold. If the list contains less than this 20% this threshold is increased by 3 dB. When the transmission rate increases we have seen that the CBR does so. This is because new resources have to be selected more frequently and the best CSRs with the smaller RSRP are occupied faster. At some point the RSRP threshold has to be increased to allow CSRs that may be used by vehicles that generate higher interference than expected. This is why with 50 pps the effect is higher and manifests earlier than 20 pps, it is considering CSRs that are being used by other vehicles very near him. With 20 pps this effect is smaller and manifests later also because the CBR is smaller. Note that this is not the only effect that is decreasing the PDR. For 50 pps at 200 m the PDR is around 80% whereas the interference/collision fails represent just an 8-9% and at 300 m the PDR is around 60% with just a 15% of errors due to interference/collision.

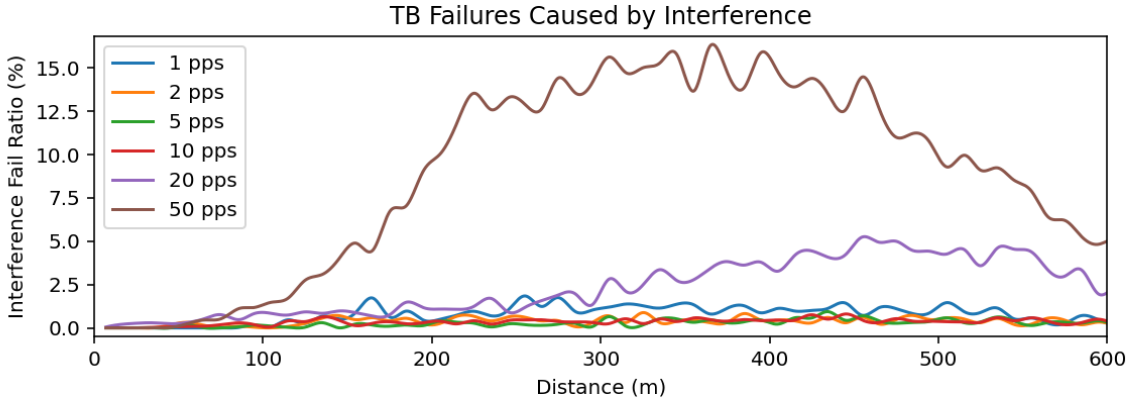

Figure 4.5 TB Failures Caused by Interference - Transmission Frequency (Fast Highway Scenario)

Furthermore, the larger is the distance between transmitter and receiver, the smaller is the interference fail ratio, an effect that specially can be seen for 50 pps. At large distances, the main reason of not receiving the TB, becomes not decoding correctly the associated SCI as seen in **Figure 4.6** where the TB reception failures associated with the lack of SCI is shown.

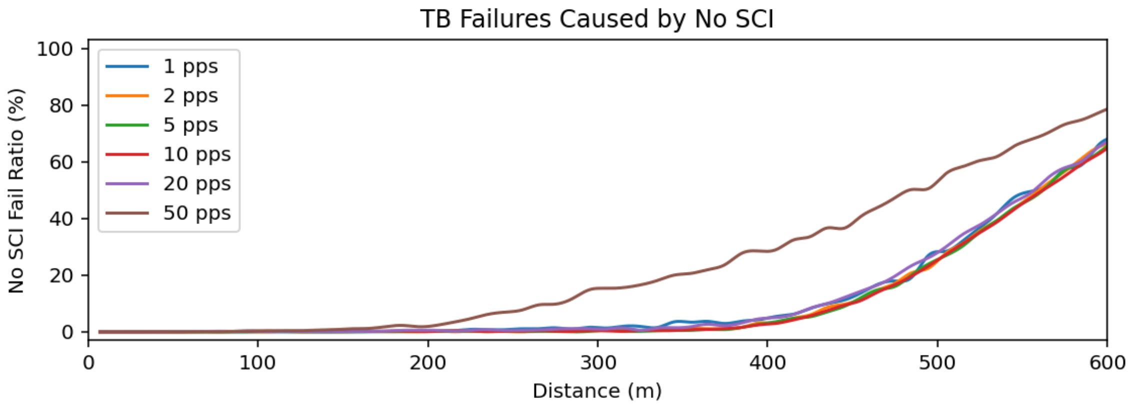

Figure 4.6 TB Failures Caused by No SCI - Transmission Frequency (Fast Highway Scenario)

There are two reasons why the SCI may not be correctly received, then the previous plot can be broken into two different plots. The first one is associated with the sensing power threshold and it is referred as unsensed ratio and it is shown in **Figure 4.7** where it is plot against the distance. This type of error just depends on the distance between both vehicles, the transmission power, the sensing power threshold and the propagation as mentioned in **Section 3.2.4**. This type of error becomes relevant at distances ≥ 300 m and affects equally to all transmission rates. The second one is associated with an interference/collision between SCIs of two different vehicles that are using the same resource to transmit and it is represented in **Figure 4.8** against the distance. The explanation of this type of error is very similar to the reason because a TB is not correctly received because of interference/collision reasons. The main difference is that the SCIs are being correctly decoded at distances where the TB were not being correctly received. To observe this phenomena the transmission rate of 50 pps is appropriate. At 200 m the 10 % of packet errors are due to TB interference, however, just a 2.5% of SCI are not being correctly

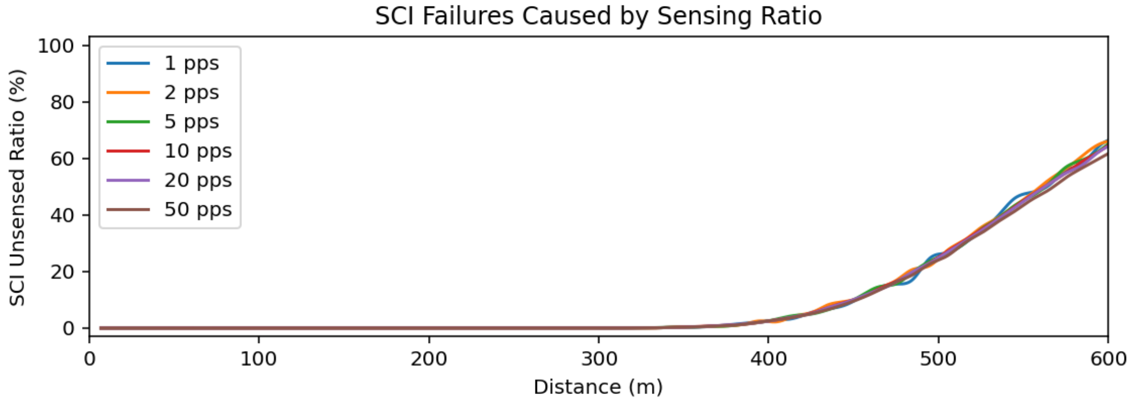

Figure 4.7 SCI Failures Caused by Sensing Ratio - Transmission Frequency (Fast Highway Scenario)

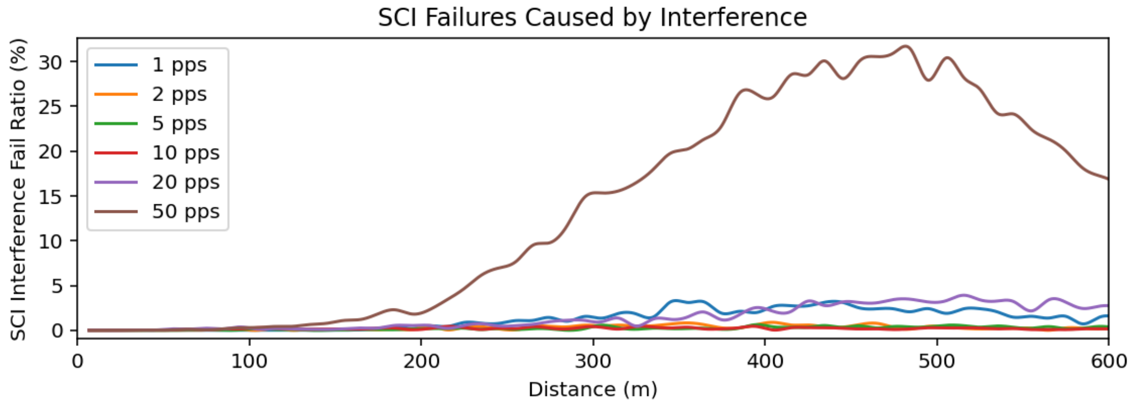

Figure 4.8 SCI Failures Caused by Interference - Transmission Frequency (Fast Highway Scenario)

received by the same reason. This has a very easy explanation and it is related with the MCS. Whereas the TBs are being sent with an MCS 7 (QPSK), the SCI is being transmitted over two RBs but with a higher protection, specifically MCS 1. This extra protection allows the SCI to be decoded for interference levels in which the TB can't be correctly decoded.

As a brief summary, the fast highway scenario performs very well at a distance of up to 300 m for any transmission rate except for 50 pps where the performance decreases very fast above 100 meters distance very punished for the TB/SCI interference errors.

Congested Highway Scenario

In **Figure 4.9** the PDR against the distance for the congested highway scenario is shown. In this scenario with a higher vehicle traffic density, specifically 70 cars/km·lane, the impact of the transmission frequency is much more evident. The performance for 50 pps abruptly decreases for distances higher than 20-30 m whereas for 20 and 10 pps the performance decreases slightly slower but goes below 80% at 80-90 m for 20 pps and around 200 m for 10 pps. A priori and before doing a deep analysis, one of the obvious reasons of such a bad performance is the higher vehicle traffic density. Remember that in **Figure 4.1** the average CBR experienced for 50 pps was nearly a 100% and this may be also one of the reasons. The idea now is to perform an analysis of the different possible transmission errors such as the one performed for the fast highway scenario.

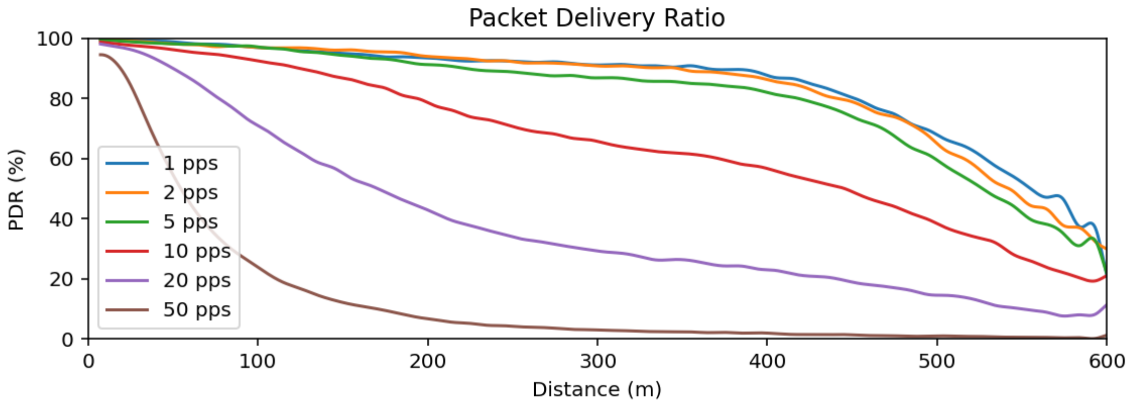

Figure 4.9 PDR vs Distance - Transmission Frequency (Congested Highway Scenario)

A part from half-duplex errors, the first type of error that has to be analyzed is the TB failures caused by interference or collision. To do so, the interference fail ratio is plotted against the distance between transmitter and receiver **(Figure 4.10)**.

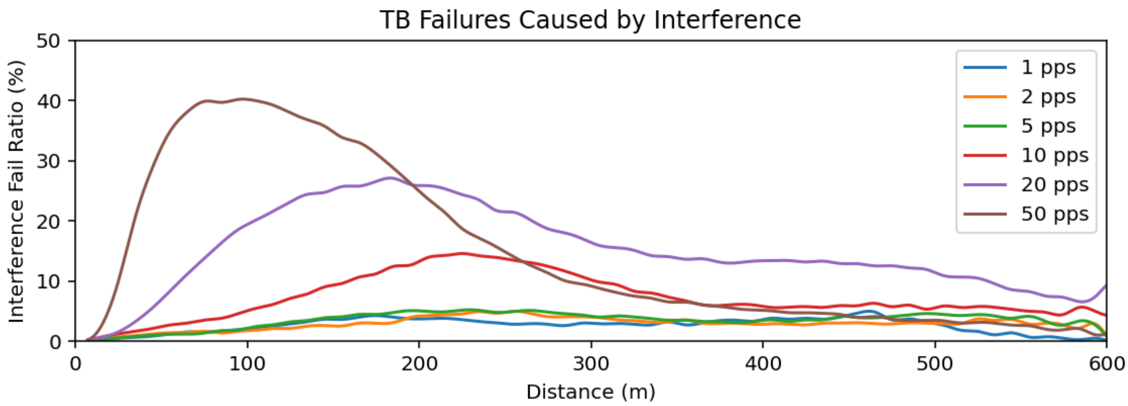

Figure 4.10 TB Failures Caused by Interference - Transmission Frequency (Congested Highway Scenario)

The first difference that it can be observed with respect to the interference fail ratio detected in the fast highway scenario **(Figure 4.5)** is the fact that the "peak" is shifted to the left (e.g. for 50 pps). This represents that the interference is taking place with smaller transmission distances than in the fast highway scenario. Furthermore, at 20 pps the shift can be noted too and at 10 pps a small peak around 220 m which was undetectable and irrelevant at the fast highway scenario can be observed now. In addition, the interference fail ratio is higher at all transmission frequencies with respect to the fast highway scenario (e.g. the peak value at 50 pps is 40% whereas at fast highway scenario was around 16%). The explanation to this phenomena is the same one as depicted in the other scenario. Considering that the vehicle traffic density is 7 times higher, the effect of considering CSRs where the interference levels may produce this type of error is amplified. Of course, increasing the number of packets per second increase the interference fail ratio. At 50 pps, the CBR was near 100% on average which represents that all CSRs, thus all the available spectrum, was being used and the vehicle had to potentially select some resources being used by other car that may cause interference and/or collisions.

As happened in the fast highway scenario, the interference fail ratio does not represent all the failure percentage at the PDR plot. The rest has to be due to failures associated with the lack of SCI that could have not been decoded either by interference/collision or by not being sensed. In **Figure 4.11** the fail ratio associated with the SCI decoding errors is shown against the distance for the usual considered transmission rates.

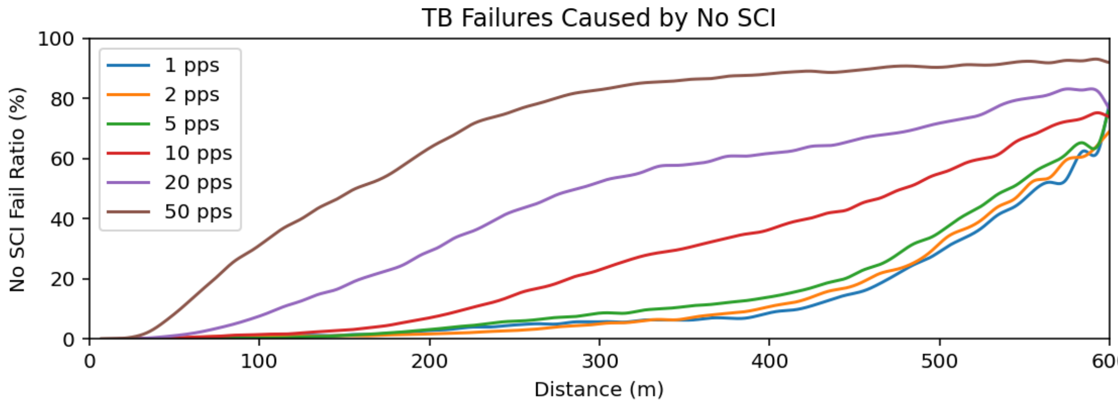

Figure 4.11 TB Failures Caused by No SCI - Transmission Frequency (Congested Highway Scenario)

The difference with respect to the fast highway **(Figure 4.6)** is notable. The error ratio starts growing at very short distances especially for 50 and 20 pps. At transmission rates from 1 to 5 pps the behaviour is very similar to the one observed at the fast highway scenario and the associated errors are mainly caused by sensing ratio errors as it can be observed in **Figure 4.12** where the ratio of unsensed SCIs is represented against the transmitter-receiver distance.

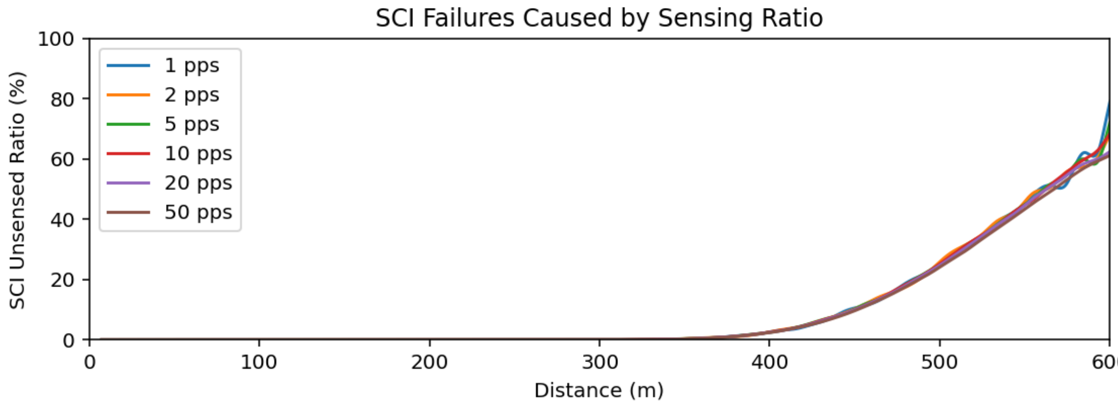

Figure 4.12 SCI Failures Caused by Sensing Ratio - Transmission Frequency (Fast Highway Scenario)

Finally, there is only one reason to explain the increasing number of SCI related errors at the whole transmission range for transmission rates from 10 to 50 pps. In **Figure 4.13** the error ratio associated to SCI interference/collisions is represented against the distance between transmitter and receiver. The explanation again is the same one mentioned in the fast highway scenario. It can be observed by comparing the SCI interference fail ratio against the TB interference fail ratio **(Figure 4.10)** that the errors caused by interference when decoding the SCI appear later in distance caused by the higher protection in terms

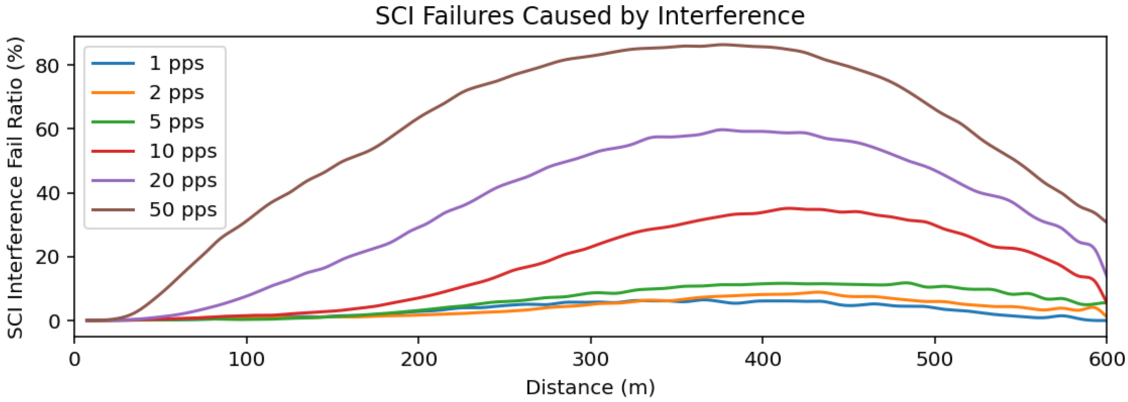

Figure 4.13 SCI Failures Caused by Interference - Transmission Frequency (Fast Highway Scenario)

of MCS for the SCI. The smaller is the transmission rate, the smaller is the fail ratio and the peak is achieved at larger distances. As aforementioned, this is caused by the sensing-based SPS and the transmission rate. Increasing the transmission rate implies more resource reservations and channel traffic and the necessity of considering potential CSRs that may cause collision. The effect of the interference decreases around 400 m of distance which is when sensing ratio errors start being the main reason of not decoding the SCIs.

With the configuration that has been used to check the effect of changing the transmission rate, it is very difficult to consider real implementations under congested highways such as the one considered in this simulation. Only would be valid to consider scenarios where the transmission rate is smaller than 5 pps and the information should be exchanged only at short distances lower than 100 m. One of the solutions in order to increase the packet delivery ratio and reduce the CBR is applying any type of congestion control mechanism (the effect of applying a congestion control mechanism such as packet dropping will be checked in **Section 4.7**). The other solution is to increase the bandwidth from 10 MHz to 20 MHz, this should reduce the channel congestion and should reduce the errors caused by interference or collisions in the same resource.

4.2. Probability of Keeping the Granted Resources

When the sensing-based SPS has been studied in **Section 2.3.1** the concept of the RC has been introduced. When this counter reaches zero, the vehicle must select new resources with a probability 1 – P where P is the probability of keeping the granted resources and can take values from 0 to 0.8. In this section, the impact of modifying this probability P is going to be analyzed for P values of 0, 0.2, 0.4, 0.6 and 0.8. When P is equal to zero the vehicle will always select new resources when the RC runs out. The rest of configurable parameters take the base configuration values.

The first analyzed metric will be the CBR to see the impact over the congestion of the channel when modifying the probability of keeping the resources. In **Figure 4.14** the CBR experienced by each car during the simulation has been averaged and plotted against the probability of keeping the resources for both fast and congested highway scenarios. The first visible fact is that changing the probability of keeping the resources has no impact on the CBR for the fast highway scenario whereas it increases as the probability does for the congested highway scenario.

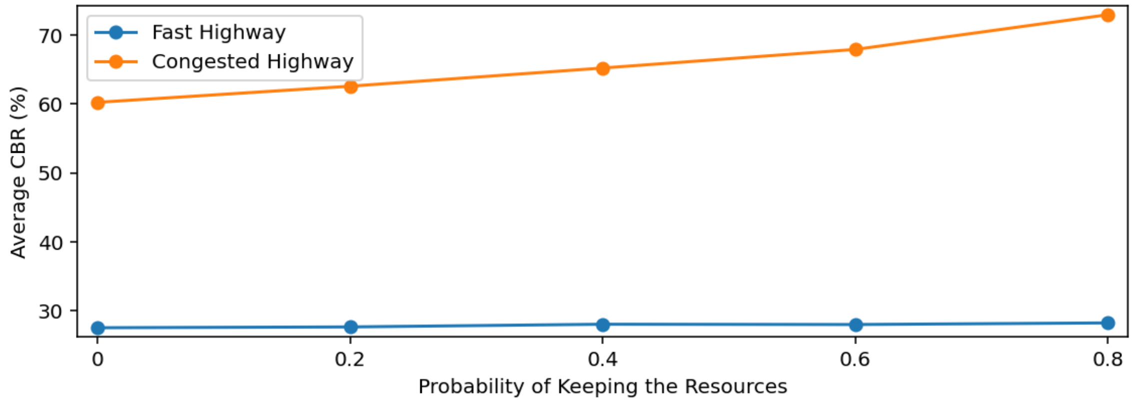

Figure 4.14 Average CBR vs Probability of Keeping the Resources

The fact that the probability of keeping the resources increases, implies that the vehicles will have to reserve new resources with a smaller probability. To have an idea of how many times a vehicle needs to break the granted resources to select new ones is represented in **Figure 4.15** where the number of times that each car has broken the granted resources has been averaged over all the cars and plotted against the probability of keeping the resources.

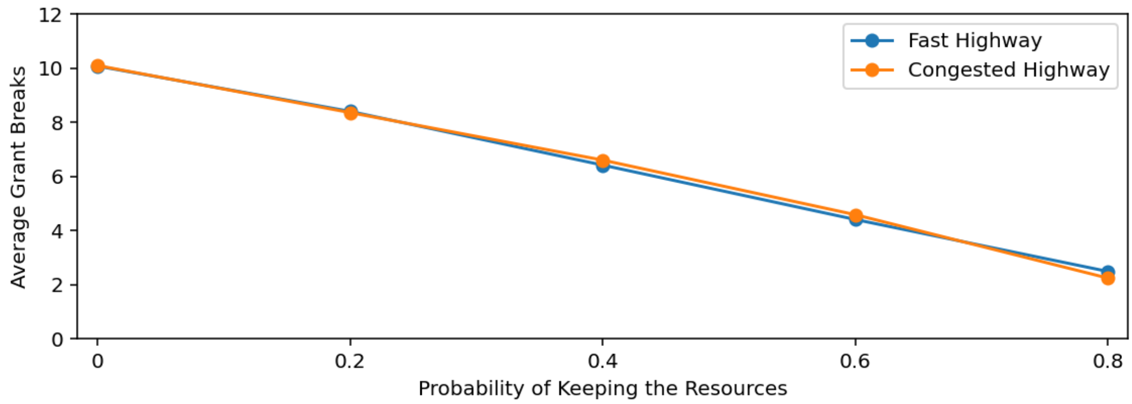

Figure 4.15 Average Grant Breaks vs Probability of Keeping the Resources

The average number of grant breaks, and therefore the number of times that the sensing-based SPS algorithm has to be performed decrements as the probability of keeping the resources increases for both fast highway and congested highway scenarios. The RC value is always the same one independently of the probability of keeping the resources since depends on the RRI which in that case is 100 ms providing an RC value that may take a random value between 5 and 15. This plot is just to have in mind the average number of times that the sensing-based SPS algorithm has to be applied.

<u>Fast Highway Scenario</u>

The PDR analysis on the fast highway scenario is shown in **Figure 4.16** where the PDR for each simulation with a different probability of keeping the resources is plotted against the transmitter-receiver distance. In that scenario, the PDR shows no dependency on the probability of keeping the resources since the performance is very similar for all the range of values. The PDR starts decreasing considerably at 400 m of distance. Just having a look at this figure it is probable that most of the errors that are decreasing the PDR from 400 m

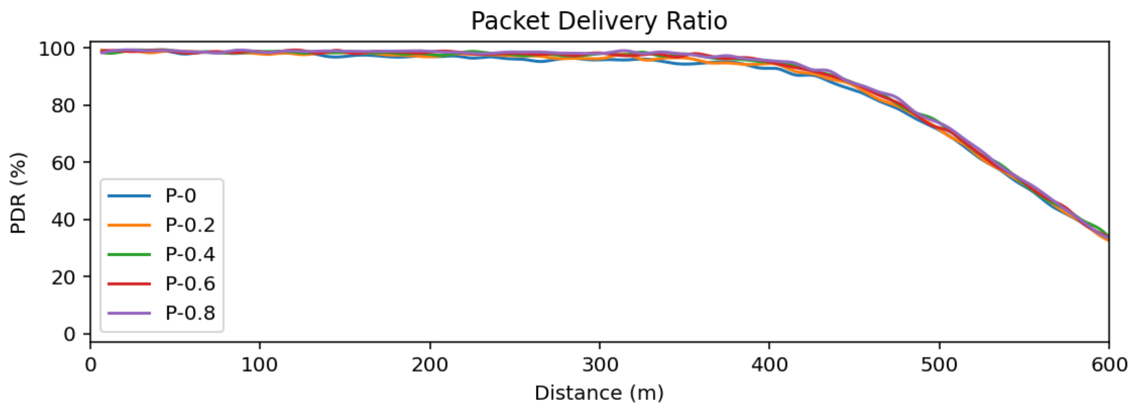

Figure 4.16 PDR vs Distance – Probability of Keeping the Resources (Fast Highway Scenario)

is due to the sensing ratio error. From this scenario there is not much information that can be extracted. Without having a look at the plots where each of type of fail is analysed separately, it is clear that changing the probability of keeping the resources has no remarkable impact on the overall performance of the system when the scenario is similar to the simulated one.

To simplify the analysis and get some insights of what I have mentioned, the SCI unsensed ratio is represented in **Figure 4.17** against the transmitter-receiver distance. It can be observed that the errors due to sensing ratio complement almost fully the reduction in the PDR from 400 m onwards. With respect to TB not decoded by interference/collision and SCI not decoded by interference/collision do not show a relation with respect to the probability of keeping the resources. Those errors represent around a 2-2.5% each of them and start to be relevant around 300 m distances.

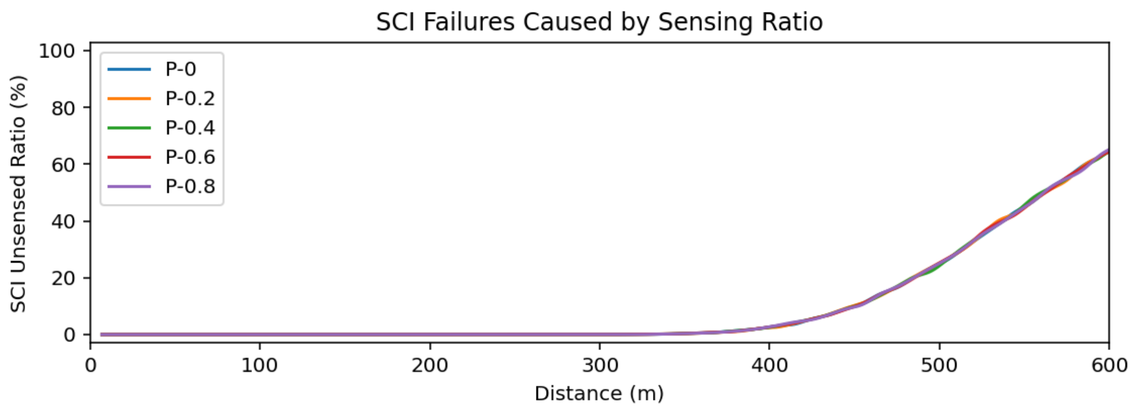

Figure 4.17 SCI Failures Caused by Sensing Ratio - Probability of Keeping the Resources (Fast Highway Scenario)

<u>Congested Highway Scenario</u>

Things change when the vehicle traffic density is increased and therefore the number of packets transmitted in the network (not because the transmission frequency has been changed). Since the CBR and therefore the channel congestion is higher than the fast highway scenario, the consequences of changing the probability of keep the resources manifest. In **Figure 4.18** the PDR is represented. As it can be observed the PDR decreases

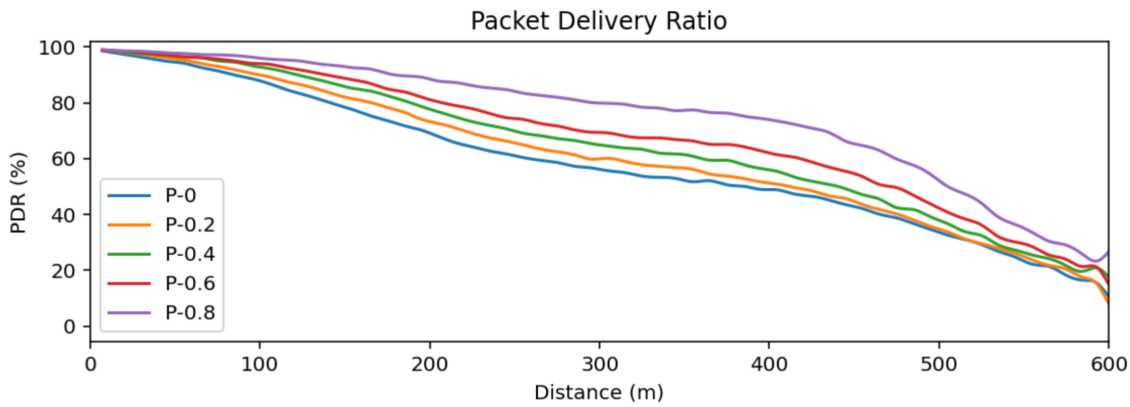

Figure 4.18 PDR vs Distance – Probability of Keeping the Resources (Congested Highway Scenario)

as the probability of keeping the resources decrease too. This can be explained by the sensing-based SPS. The higher is the number of times that the vehicles have to select new resources, the more likely is to select resources that have been previously used by other vehicles with potential interference probability.

To check the aforementioned fact, the TB interference fail ratio has been plotted for different probabilities of keeping the resources versus the distance between the transmitter and the receiver **(Figure 4.19)**.

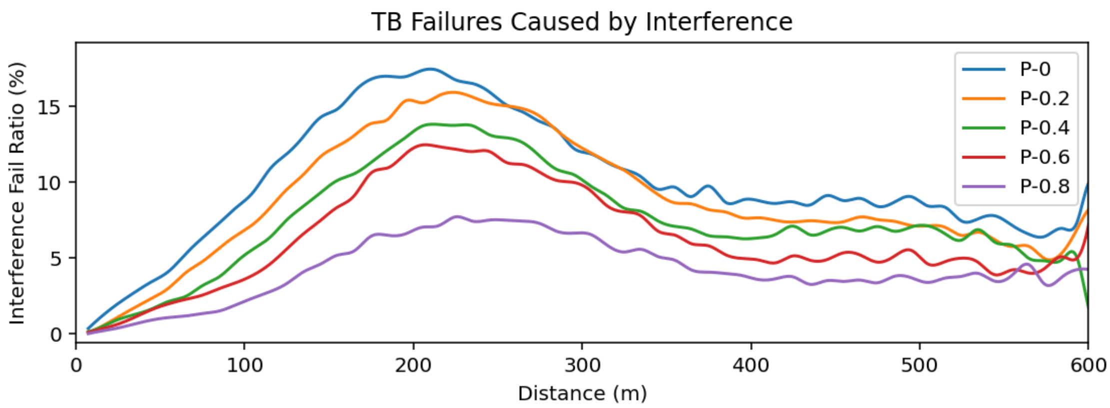

Figure 4.19 TB Failures Caused by Interference – Probability of Keeping the Resources (Congested Highway Scenario)

With 100% of probability of having to select new resources the maximum interference ratio represents around the 18% of the total errors at 200 meters of distance. However, when increasing the probability of keeping the resources until an 80% this peak is flattened and achieves its maximum around 7-8% of interference fail ratio at 250 m between the transmitter and receiver. At short distances the interference is the main problem. When the vehicle has to select new resources every time the reselection counter reaches zero, it does select one CSR of the well-known list of best CSRs. Considering that the vehicles must select new resources very frequently, the quality of possible CSRs candidates start decreasing. A part from that, due to the vehicle traffic density, two vehicles have a certain probability of choosing the same CSR to transmit generating a potential interference. As a result, when the vehicles reduce the probability of having to select new resources, the probability of having an interference is reduced. Mainly, this happens because there will be less reselections of resources. However, increasing the probability that a vehicle keep the granted resources implies a higher CBR as shown in **Figure 4.18** thus there is a trade-off since with higher transmission rates this may be a potential problem.

The TB failures caused by incorrect reception of the SCI is shown in **Figure 4.20** where this type of error becomes more relevant as the distance between transmitter and receiver increases. As it is already known from other analysed simulations, the sensing-based error becomes relevant at distances between vehicles higher than 400 m. The plot is not shown since it takes the shape of the fast highway scenario seen in **Figure 4.17** and does not depend on the probability of keeping the granted resources as observed.

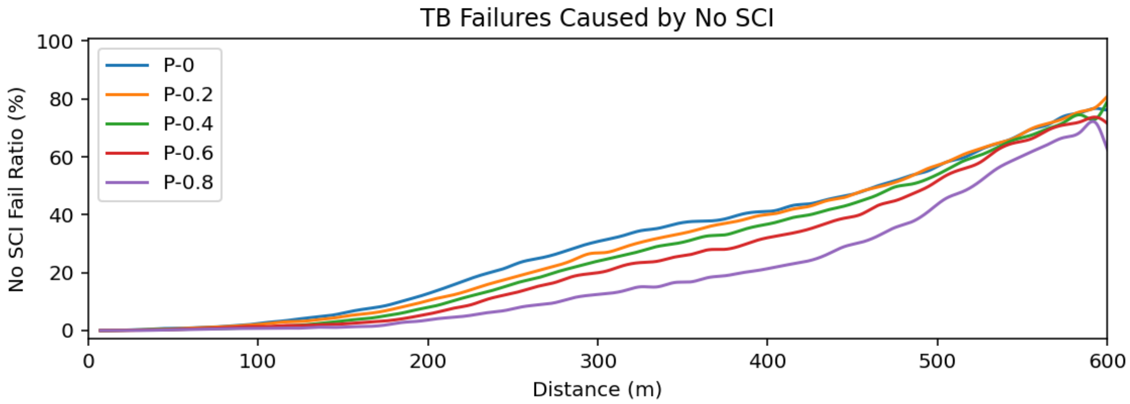

Figure 4.20 TB Failures Caused by No SCI – Probability of Keeping the Resources (Congested Highway Scenario)

Finally, the SCI failures caused by interference/collision are shown in **Figure 4.21** where it can be observed a very similar behaviour as in **Figure 4.19** in terms of fail ratio against probability of keeping the resources. The unique difference with the interference fail ratio of the TBs is that the peak it is shifted to further distances. As already explained this is caused by the extra protection that the SCI contains.

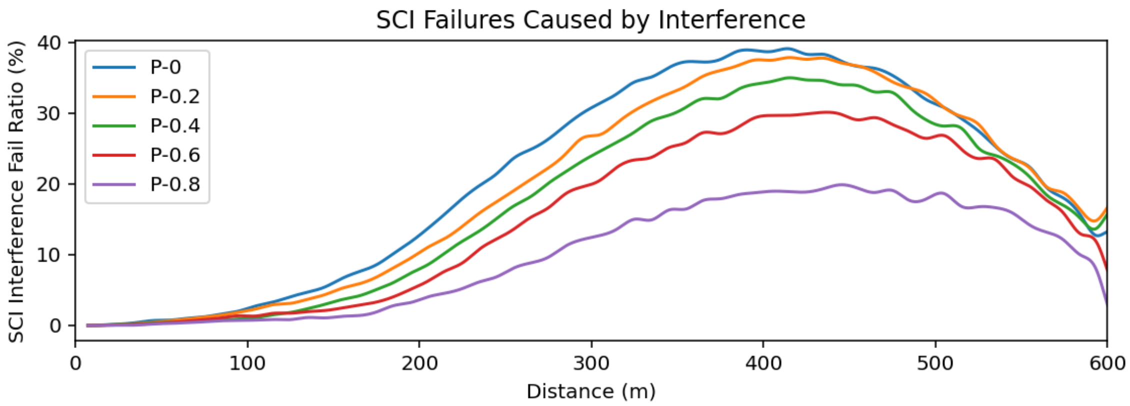

Figure 4.21 SCI Failures Caused by Interference – Probability of Keeping the Resources (Congested Highway Scenario)

4.3. Modulation and Coding Scheme

The main intention of this section is to analyze the impact of changing the MCS from the base QPSK that has been used for the rest of the simulations to the 16QAM and 64QAM. The main idea is to change the subchannelization as a function of the MCS always trying to maximize the efficiency in terms of assigned bandwidth to a user. In addition the impact will be analyzed for the most demanding transmission rates: 10, 20 and 50 pps. In **Section 3.2.3** it has been explained how the number of RBs that were necessary to transmit the packet is calculated based on the MCS Index. Considering that the packet size is 190 B, just one subchannel to transmit and having a look at table 7.1.7.2.1-1 in [17], the following configurations are defined for each MCS:

- **QPSK**: The MCS Index considered is 7 as the default configuration. With the actual packet size, 13 RB are needed to transmit in one TB the packet plus 2 RBs to transmit the SCI. The channel configuration will consist in 16 RBs per subchannel with 3 subchannels as the base configuration too.
- **16QAM**: The MCS Index considered is 14 which corresponds to a TBS Index 13. Considering 190 B of packet and this TBS Index, 6 RBs are needed to transmit the packet in just one TB. Based on the premise that the channel bandwidth is 10 MHz and the efficiency must be maximized, the new sidelink configuration will consist in 8 RBs per subchannel with 6 subchannels. When a vehicle transmits the packet with 16QAM it will use only 8 RBs (i.e. 6 RBs for the TB and 2 RBs for the SCI) maximizing the utilization of the subchannel.
- **64QAM**: The MCS Index considered is 20 which corresponds to a TBS Index 18. With the considered packet size, 4 RBs are needed to transmit the packet in just one TB. As explained for the 16QAM case, the subchannelization was modified to improve the efficiency. The new channel configuration consists in 6 RBs per subchannel with 8 subchannels. When the vehicle transmits using 64QAM it will only use 6 RBs (i.e. 4 RBs for the TB and 2 RBs for the SCI) thus maximizing the utilization of the assigned subchannel.

Taking the aforementioned facts into account the first metric that it is going to be analyzed as done in previous simulations is the CBR to check the channel congestion. For sake of clarity this time it has been separated in two plots, one considering the fast highway scenario **(Figure 4.22)** and another one for the congested highway scenario **(Figure 4.23)**. In both plots the CBR is represented against the transmission rate for QPSK, 16QAM and 64QAM modulations. For both cases increasing the transmission rate increases the CBR, nothing new here since this effect has been considered and explained in **Section 4.1**. However, increasing the data rate (i.e. the MCS) and therefore reducing the coding rate and protection of the data, reduces the channel congestion. This effect is logic and it is a consequence of changing the subchannelization scheme of the channel. When transmitting the packet with QPSK, one subchannel of 16 RBs is needed and therefore in the same subframe, just two vehicles can transmit, each of them using one of the remaining subchannels. With 16QAM and 64QAM the number of subchannels is higher since less RBs per subchannel are needed to perform the packet transmission. With 64QAM, 7 subchannels in the same subframe remain for 7 vehicles that can perform the transmission in the same subframe. In the case of 16QAM, 5 vehicles can perform transmission at the same subframe. The main consequence is that the channel congestion is reduced since the vehicles need less bandwidth as the modulation increases. Note that in case of keeping

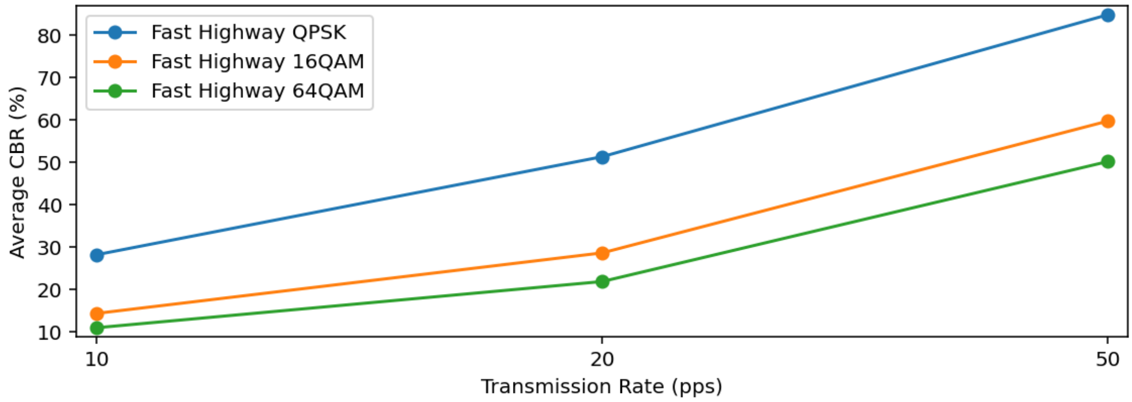

Figure 4.22 Average CBR vs Transmission Rate – MCS (Fast Highway Scenario)

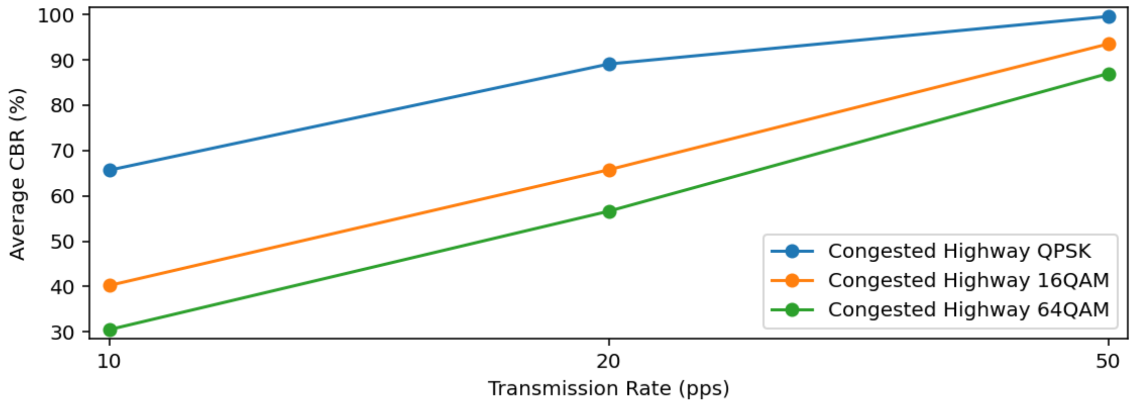

Figure 4.23 Average CBR vs Transmission Rate – MCS (Congested Highway Scenario)

the original subchannelization scheme of 16 RBs per subchannel and 3 subchannels, the vehicles will be using one subchannel where more than half of the RBs are not used and can't be exploited by any vehicle.

<u>Fast Highway Scenario</u>

The selection of the MCS under different transmission rates, will have an impact on the overall performance of the system. This can be checked by means of the PDR First, the results associated to the fast highway scenario are presented. In **Figure 4.24**, **Figure 4.25**, **Figure 4.26**, the PDR is plotted against the distance between transmitter and receiver for QPSK, 16QAM and 64QAM modulations, considering 10, 20 and 50 pps respectively. At 10 pps, changing the modulation does not change the PDR since the performance is very similar for the three modulations. However, as the transmission rate increases, the QPSK starts showing a worse performance especially at distances beyond 200 m and with 50 pps in benefit of 64QAM modulation which reveals the best performance at far distances. It may seem a little bit contradictory to see a better performance with an MCS that provides better data rate but at the same time less protection to the data. The expected effect would be a worse performance with 64 QAM under situations of large distances between transmitter and receiver. However, the fact that the subchannelization scheme has changed when changing the MCS is the responsible of this effect. The channel congestion is reduced as has been explained when talking about the CBR. To fully understand this, the TB failures

Figure 4.24 PDR vs Distance – MCS – 10 pps (Fast Highway Scenario)

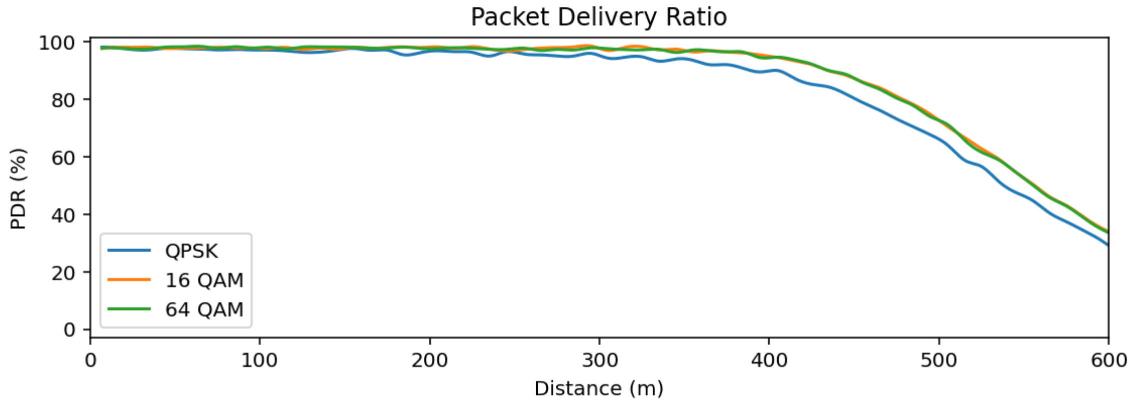

Figure 4.25 PDR vs Distance – MCS – 20 pps (Fast Highway Scenario)

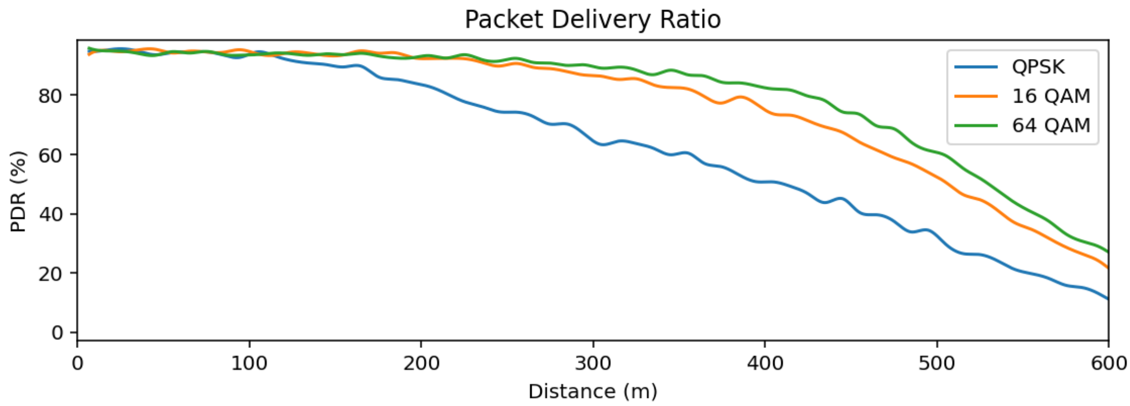

Figure 4.26 PDR vs Distance – MCS – 50 pps (Fast Highway Scenario)

caused by interference for 50 pps transmission rate is represented in **Figure 4.27** whereas the SCI failures caused by interference for 50 pps is represented in **Figure 4.28**. The observed effect is very similar to the one observed when increasing the transmission rate in its analysis in **Section 4.1**. When the channel congestion is reduced by increasing the MCS the number of failures caused by interference or collisions is reduced directly affected by the number of occupied CSRs.

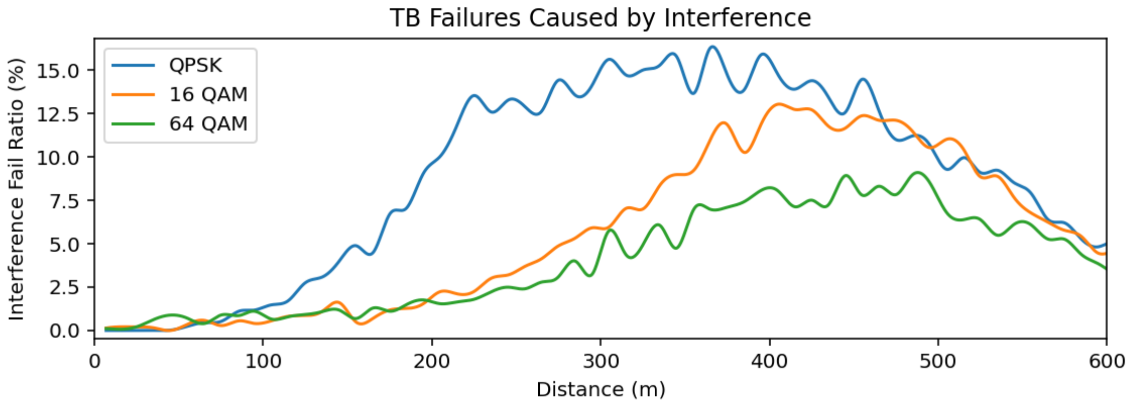

Figure 4.27 TB Failures Caused by Interference – MCS (Fast Highway Scenario)

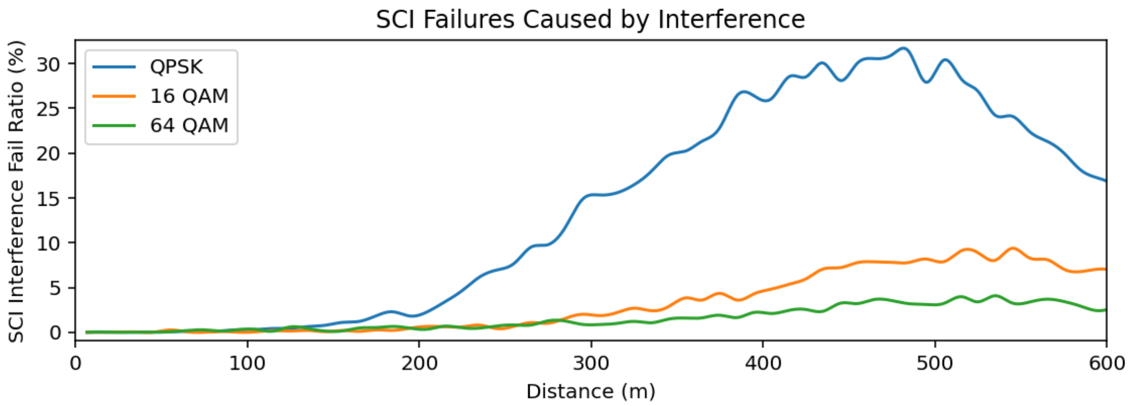

Figure 4.28 SCI Failures Caused by Interference – MCS (Fast Highway Scenario)

In the aforementioned section, it has been explained that increasing the number of pps was increasing the channel congestion and therefore the vehicles when selecting new resources, had to select resources with potential opportunity of collision. The effect is very similar with the MCS, as the quality of CSRs when selecting new resources at 64QAM is much better than the observed with QPSK directly affected by the congestion of the channel. Note that in **Figure 4.28**, the MCS represented has nothing to do with the MCS of the SCI which is always QPSK but with the MCS of the TB.

Congested Highway Scenario

The congested highway scenario considers a vehicle traffic density which is higher as the number of transmitted packets are. In **Figure 4.29**, **Figure 4.30**, **Figure 4.31**, the PDR is plotted against the distance between transmitter and receiver for QPSK, 16QAM and 64QAM modulations, considering 10, 20 and 50 pps respectively. The observed effect in the fast highway scenario is the same one observed for the congested scenario but with the PDR according to what has been seen in other analysis. For 10 pps, 16QAM and 64QAM outperform the QPSK by offering a much better PDR. At 20 pps the difference between 16QAM and 64QAM becomes relevant in favour of the latter. At 50 pps, where the worst PDR has been observed in **Section 4.1**, 64QAM improves the PDR but not enough to consider further distances than the QPSK case since with a PDR of 80%, which is relatively low, the difference is no more than 10-20 m.

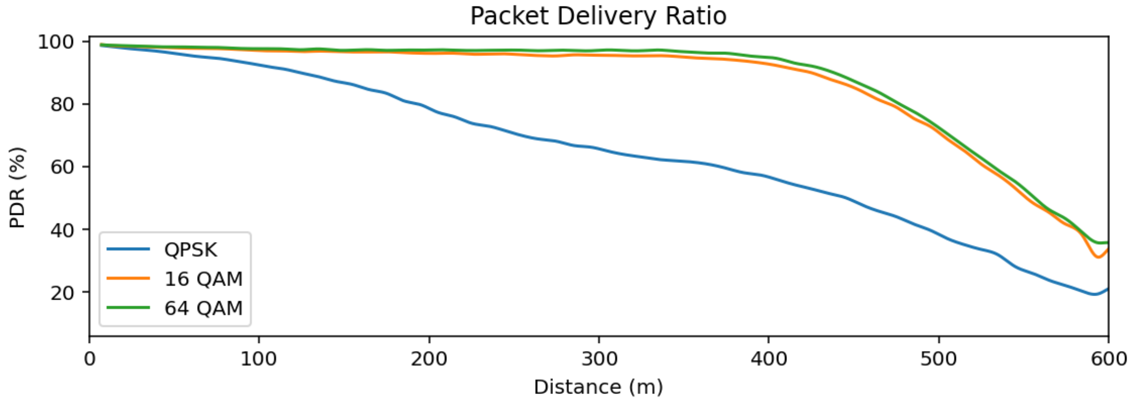

Figure 4.29 PDR vs Distance – MCS – 10 pps (Congested Highway Scenario)

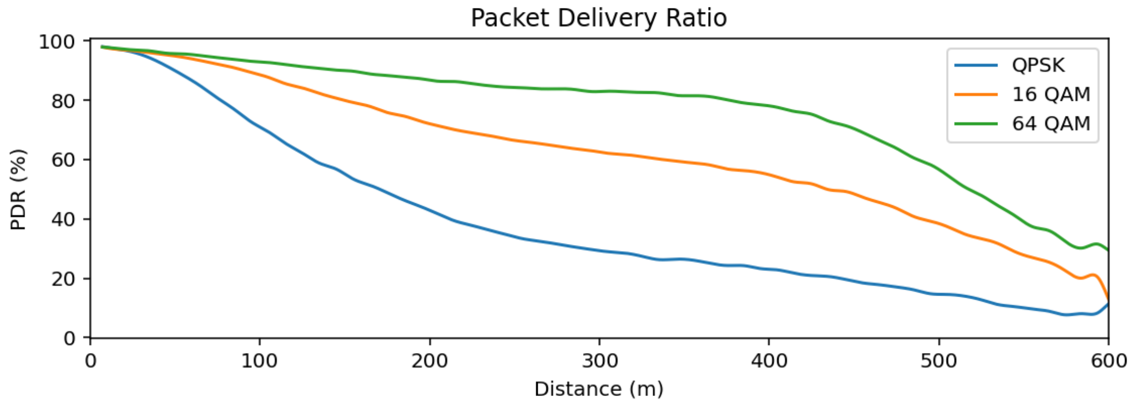

Figure 4.30 PDR vs Distance – MCS – 20 pps (Congested Highway Scenario)

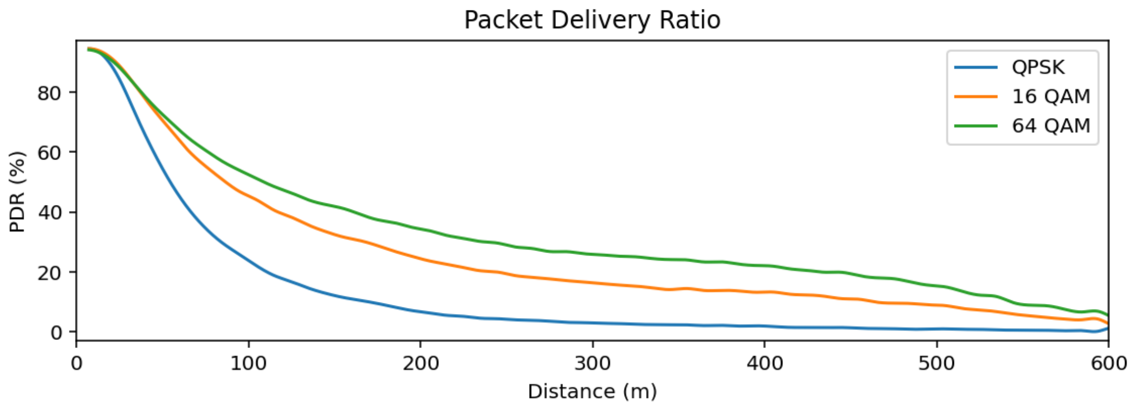

Figure 4.31 PDR vs Distance – MCS – 50 pps (Congested Highway Scenario)

In **Figure 4.32** the TB failures associated to interference or collision is plotted against the transmission distance between transmitter and receiver, whereas in **Figure 4.33** the SCI failures associated to the interference or collision is plotted against transmitter-receiver distance too. The observed behaviour at the TB failures caused by interference is the expected one. At distances further than 220 the QPSK modulation produces less interference errors than 16QAM and 64QAM. These modulations have a floor error (the latter higher than the first one) which was shadowed by the low congestion of the channel

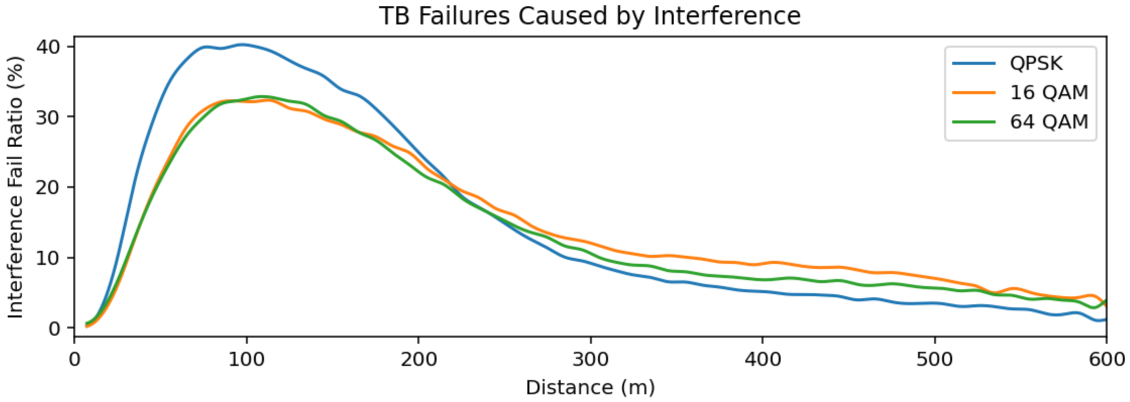

Figure 4.32 TB Failures Caused by Interference – MCS (Congested Highway Scenario)

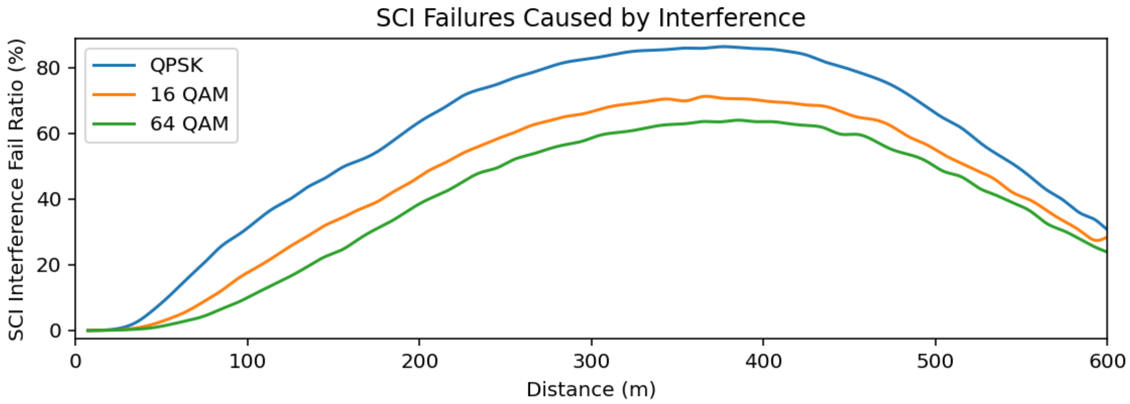

Figure 4.33 SCI Failures Caused by Interference – MCS (Congested Highway Scenario)

as explained in the fast highway case. This floor error is directly related with the protection of the data which is smaller as the modulation increases. Beyond a certain distance, the interference produced with 16QAM and 64QAM is high enough to prevent the TB from being decoded, whereas the extra protection of the QPSK provides a correct decoding. Finally, when analysing the SCI failures caused by interference, nothing changes since the protection of the SCI is always QPSK and the ratio of interference directly depends again on the congestion of the channel.

In a nutshell, apparently increasing the modulation always offer a better performance. However, from the theory, it is known that higher modulation implies less data protection and this has an impact on the overall performance of the system. It would be interesting to test again this under different conditions such as less demanding scenarios with a smaller number of vehicles not limited by capacity to check if at some point, with transmission rates of 50 pps, the QPSK becomes more reliable at large distances.

4.4. Subchannelization and Packet Size

The C-V2X sidelink channel may adopt different subchannelizations even considering the same channel bandwidth (i.e. the same number of available RBs). Changing the number of subchannels and consequently the number of RBs per subchannel apparently may have an impact on the overall system. In **Table 4.1** the number of subchannels that are needed to perform transmission in one TB for 190 B and 300 B for different subchannelization schemes is represented. The MCS remains the one specified in the base configuration, i.e. MCS Index 7 with QPSK modulation. The packet size is a variable that has been added to this study because it is related to the subchannelization. When changing the packet size, the number of RBs needed to transmit the packet changes as the number of subchannels does. For example, with a subchannelization of 16 RBs per subchannel and 3 subchannels the 190 B packet can be transmitted in one subframe (i.e. 13 RBs for the TB plus 2 RBs for the SCI). Nevertheless, for 300 B, 22 RBs are needed to perform the transmission of the SCI+TB and two subchannels must be selected. In that case, the vehicle will occupy 32 RBs (i.e. 2 subchannels).

Table 4.1 Subchannels needed to transmit vs Subchannelization and Packet Size

	Packet Size	190 B	300 B
	RBs to transmit	13 RBs	20 RBs
SUBCHANNELIZATION (RBs/subchannel – subchannel)	24 - 2	1 Subchannel (24 RBs)	1 Subchannel (24 RBs)
	16 - 3	1 Subchannel (16 RBs)	2 Subchannels (32 RBs)
	8 - 6	2 Subchannels (16 RBs)	3 Subchannels (24 RBs)

Before going into detail with the results, an aspect related with the sensing-based SPS and the resource candidates must be explained. This will help to have a better understanding of the results obtained. When the vehicle is going to select resources through the sensing-based SPS it generate the CSRs list depending on the number of subchannels that needs to perform the transmission. Two different subchannelizations may imply the same number of CSRs located in the same position. To better understand this an example is given **(Figure 4.34)**. In this figure, only 10 subframes are considered for sake of simplicity. Note that this block can be extended to meet the selection window necessary in each case. Not all the CSRs are represented in that picture for better understanding. For sake of simplicity, let's consider 190 B of packet size and a transmission rate of 10 pps. For the subchannelization with 16 RBs per subchannel and 3 subchannels, the vehicle will have an initial list of 300 CSRs in the selection window (i.e. 3 CSRs per subframe where each CSR represents 1 subchannel). Now, if the subchannelization with 8 RBs per subchannel and 6 subchannels is considered, since the vehicle needs 2 subchannels of 8 RBs each one to perform the transmission, the considered CSR will occupy two subchannels. Therefore, the vehicle will also have an initial list of 300 CSRs in this case. When the CSRs

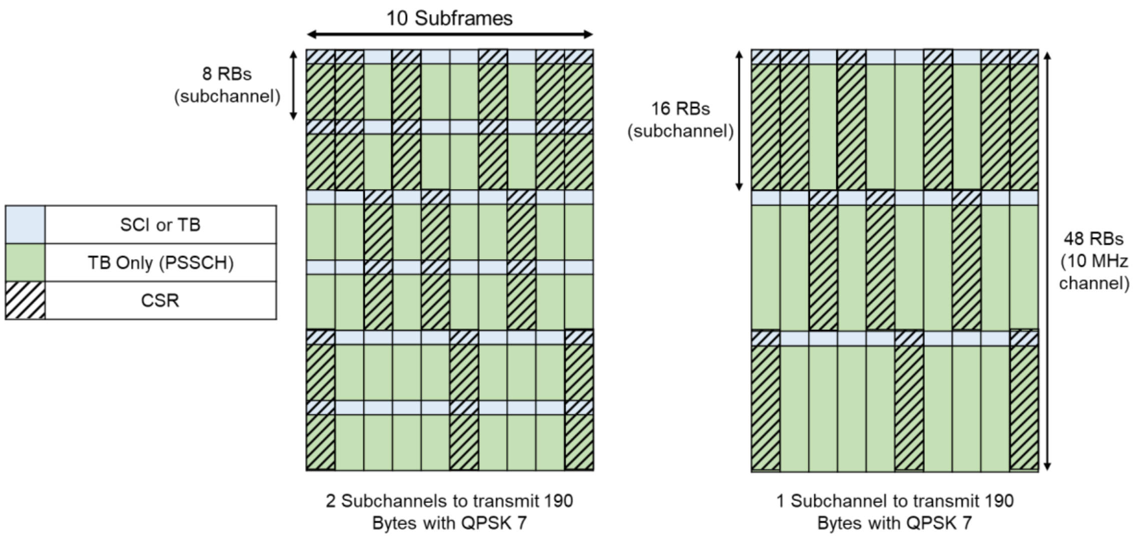

Figure 4.34 Example of CSRs based on two different subchannelization

are generated, the vehicle considers groups of two subchannels, starting from the first one in the subframe. Therefore, it is not possible to find CSRs with subchannel index 2 and 3, or 4 and 5 which would leave only a subchannel that could not be used by this car. The same applies for different subchannelization and number of subchannels needed to transmit.

Even though apparently these are two different configurations, in terms of transmission are exactly the same. If the vehicle selects the CSR number 1 (i.e. the first CSR of the first subframe), for both configurations it will be transmitting the packet with the same amount of resources, the same bandwidth and at the same frequency. This is also the case of the transmission of a 300 B packet with 24 RBs per subchannel with 2 subchannels and 8 RBs per subchannel with 6 subchannels.

The first study item will be the average CBR considering the different combinations depicted in **Table 4.1**. The obtained results are represented in **Figure 4.35** considering both fast and congested highway scenarios.

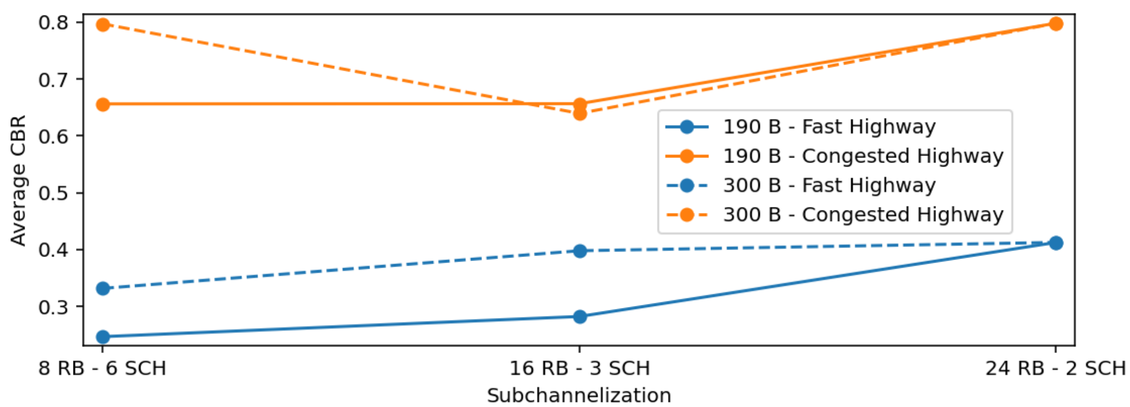

Figure 4.35 Average CBR vs Subchannelization and Packet Size

After the explanation that revealed the fact that in terms of CSRs 16 RBs and 8 RBs per subchannel configurations are equal for 190 B and 24 RBs and 8 RBs per subchannel are equal for 300 B transmission, an expected conclusion would be that in these cases the average CBR should be equal. However as it can be observed in the plot, this is not the case. Even though the vehicle may use the same CSR, the CBR is an RSSI measurement performed per subchannel. When the vehicle measures the CBR, even though the vehicle transmits in the same CSR for the aforementioned cases, in the case of one subchannel the RSSI will be measured over 16 RBs whereas when the transmission is performed in two subchannels, it will be measured over 8 RBs. As a consequence, the power per subchannel (i.e. the RSSI) will be half in the second case with a higher probability of being above the RSSI threshold for the 16 RBs case (i.e. interpreted as busy). This is why with 190 B, for 16 RBs per subchannel the experienced average CBR is higher than for the 8 RBs per subchannel case. The same explanation applies for the transmission of a 300 B packet with 24 RBs per subchannel with 2 subchannels and 8 RBs per subchannel with 6 subchannels. The average CBR is the same for the transmission of a 190 B or 300 B packet with a subchannelization of 24 RBs per subchannel since both cases are using the same amount of RBs to transmit over 1 subchannel. In addition, both cases have the same CSRs.

Fast Highway Scenario

The analysis of the CSRs has given a clue of what can be expected in terms of PDR for those cases where the list of CSRs is the same one. In **Figure 4.36** the PDR with a transmission of 190 B for three different subchannelization schemes against the transmitter-receiver distance whereas in **Figure 4.37** the transmission of a 300 B is considered.

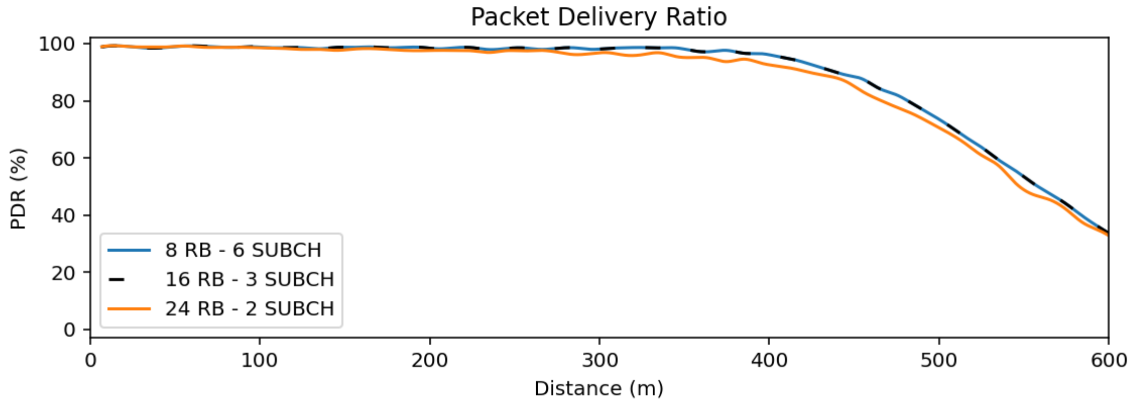

Figure 4.36 PDR vs Distance – 190 B (Fast Highway Scenario)

For 190 B transmission only two subchannelizations are visible in the plot. This is because the PDR is exactly the same one for the configuration of 8 RBs per subchannel with 6 subchannels and 16 RBs per subchannel with 3 subchannels and therefore the two lines overlap in **Figure 4.36**. The explanation behind this result is the one given at the beginning of this section. As the number of CSRs is the same one with the same granularity, there is no difference between using one configuration or the other. The PDR is worse for the 24 RB per subchannel and 2 subchannels configuration, the number of CSRs is smaller and this causes a degradation in terms of PDR. In addition, with this configuration, the vehicle is using a higher bandwidth than needed, since 15 RBs would be enough to transmit the pair SCI+TB but it is using 24 RBs for transmission.

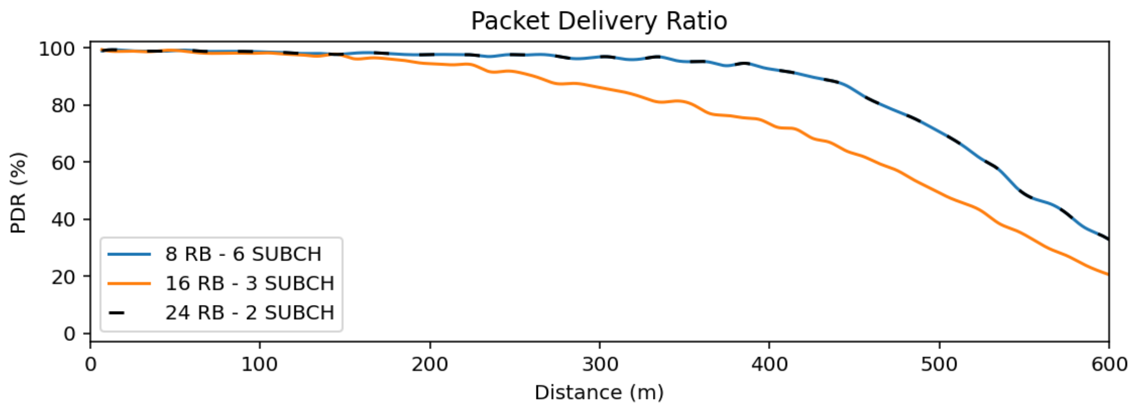

Figure 4.37 PDR vs Distance – 300 B (Fast Highway Scenario)

When the packet size is 300 B a similar behaviour is observed in the plot. Again there are two configurations that are providing the same PDR which are 8 RBs per subchannel with 6 subchannels and 24 RBs per subchannel with 2 subchannels. The reasoning is the same one as for the pair of subchannelizations mentioned in the 190 B packet size case and also has been mentioned at the beginning of the section. For both subchannelizations, the packet is being transmitted using a CSR of 24 RBs, one includes 3 subchannels whereas the other one just 1. The PDR is highly penalized when the chosen configuration is 16 RBs per subchannel with 3 subchannels. To transmit the 300 B packet with this configuration two subchannels are needed. When the vehicle generate the list of possible CSRs, there is always one subchannel that it is not used since two are needed to generate a CSRs. This implies that from a total of 48 RBs, only 32 RBs can be used, so a third part of the spectrum cannot be assigned to any vehicle. In addition there is just one CSR per subframe which contains 32 RBs, more than the 22 RBs needed to transmit the SCI+TB pair. This is a potential waste of resources.

Congested Highway Scenario

As seen in previous analysis, increasing the vehicle traffic density implies an important reduction in terms of PDR. In that case, there is no exception as the PDR decreases with respect to the one observed in the fast highway scenario. In **Figure 4.38** the PDR against different subchannelizations and the transmitter-receiver distance is represented for a 190 B transmission whereas in **Figure 4.39** it is represented for a 300 B transmission.

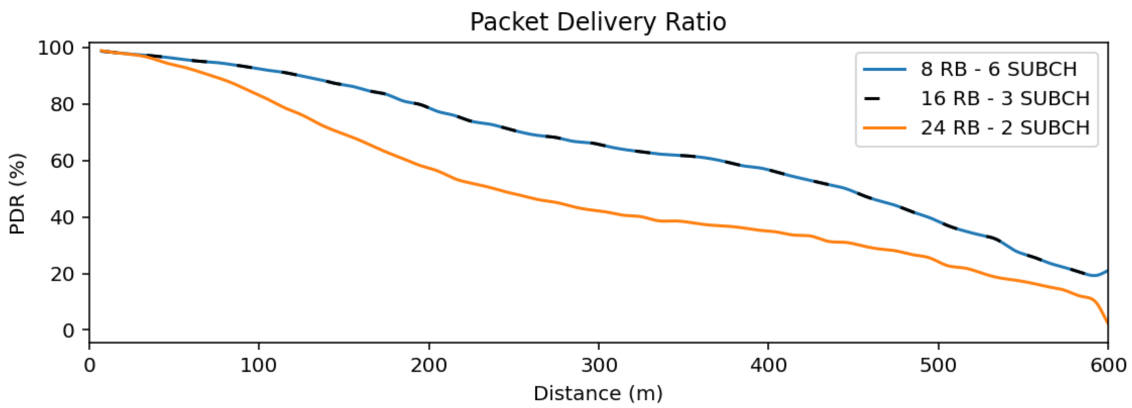

Figure 4.38 PDR vs Distance – 190 B (Congested Highway Scenario)

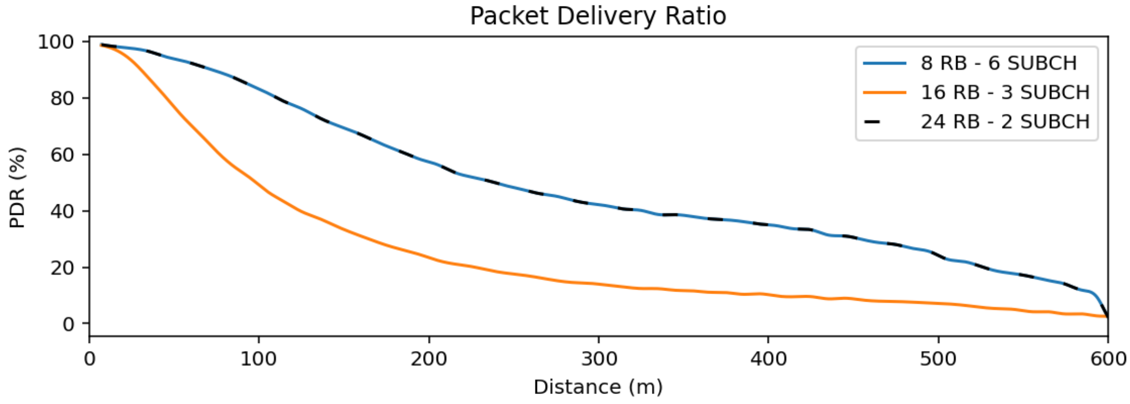

Figure 4.39 PDR vs Distance – 300 B (Congested Highway Scenario)

Nothing changes with respect to the analysis of which is the most appropriate subchannelization for each of the transmission rates. Neither does the fact that the already well known pair of subchannelizations for 190 B and 300 B provide exactly the same PDR. The new idea that can be introduced is the fact that increasing the vehicle traffic density and indirectly the number of transmitted packets, the subchannelization schemes that reduced the PDR at the fast highway scenario suffered from a major degradation in terms of PDR.

The conclusion is that once an MCS and packet size is decided, the subchannelization used in that network (e.g. the section of the road) must be appropriately chosen trying to maximize the efficiency in terms of RBs (i.e. selecting a combination of number of subchannels and RBs per subchannel that leaves the lowest possible free RBs) which indirectly implies maximizing the number of CSRs. This helps to reduce the channel congestion as well as improve the PDR.

However, for networks where there is more than one application with different packet sizes this may not be the correct approach. Anyway, this would require from a more elaborated study in future works.

4.5. Transmission Power

When the LTE-V standard has been defined, it has been stated that the maximum transmission power for the UE is 23 dBm. However, in LTE there are also UEs that transmit at 20 dBm. At the base configuration **(Section 3.2.3)** the transmission power for all the vehicles has been set to 23 dBm. The intention of this section is to see the impact of reducing in 3 dB the transmission power of the vehicles mainly in terms of PDR. In advance, it is known that with lower transmission power, the maximum transmission distance is reduced, but at the same time the generated interference may be weaker and help to increase the PDR at short distances. The rest of parameters take the base configuration values.

In **Figure 4.40** the average CBR is represented for the fast and congested highway scenarios against the transmission power. There is almost no difference with respect to the CBR when transmitting at 20 or 23 dBm. For the fast highway scenario the average CBR is a little bit smaller because when the vehicle has to calculate the CBR, the probability of detecting as occupied one subframe increases when the transmission power does so. This

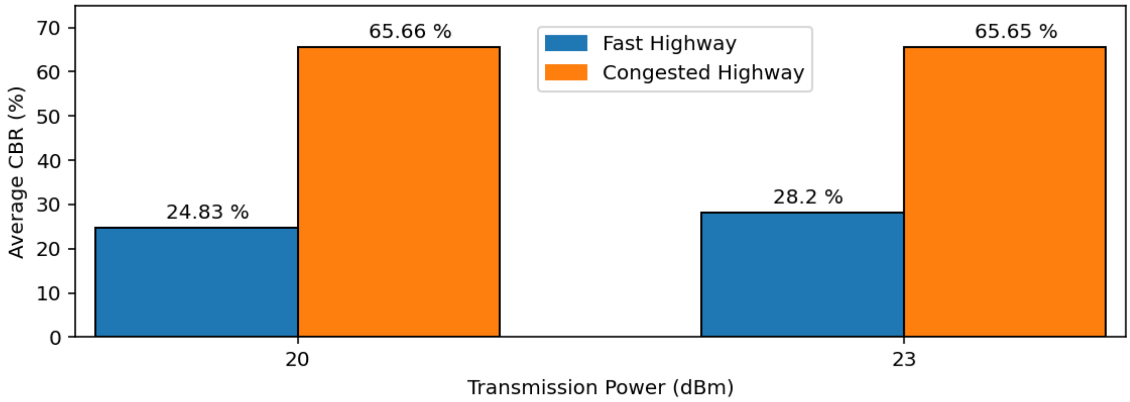

Figure 4.40 Average CBR vs Transmission Power

small variation is not detected in the congested scenario since the vehicle traffic density is higher and all the cars experience a very similar average CBR for both transmission powers.

Fast Highway Scenario

The PDR against the distance between the transmitter and receiver for 20 and 23 dBm is represented in **Figure 4.41**. Reducing the vehicle transmission power from 23 to 20 dBm has no impact for transmission distances below 300 m where the performance is very similar whereas beyond 300 m, the PDR decreases faster and transmitting at 20 dBm is clearly worse. Without having a look at the rest of plots it is clear that most of the errors at distances beyond 300 will be due to unsensed SCIs. Reducing the transmission power reduces the probability of correctly receiving an SCI at a given distance. Due to this fact, the errors caused by unsensed SCIs increase when reducing the transmission power. To really know the main reason that causes the PDR to be worst in the low power case it is necessary to make a deep analysis of each type of error. The first one is the already well-known TB error caused by interference/collision.

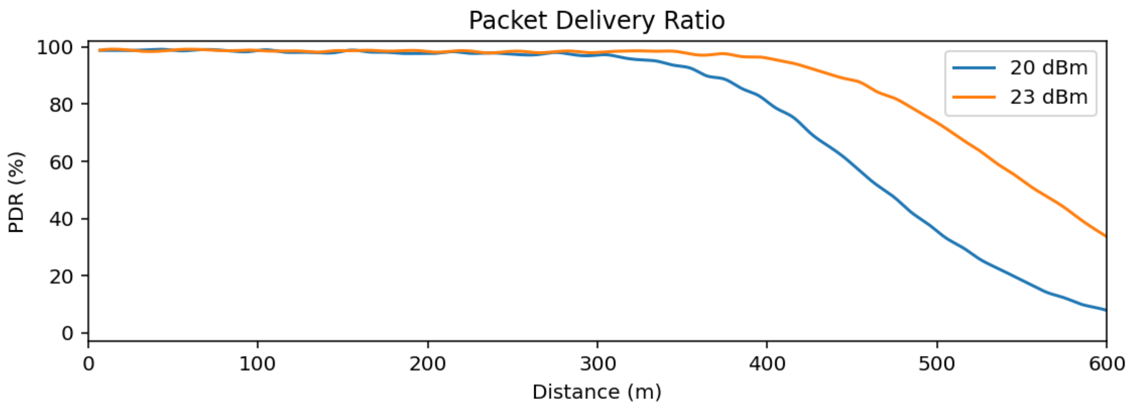

Figure 4.41 PDR vs Distance – Transmission Power (Fast Highway Scenario)

The interference fail ratio is represented against the transmitter-receiver distance in **Figure 4.42**. For both scenarios, the percentage of failures caused by this reason is very small in comparison with other causes that will be analysed later on. Therefore, this is not the main reason to justify the PDR reduction when changing to 20 dBm.

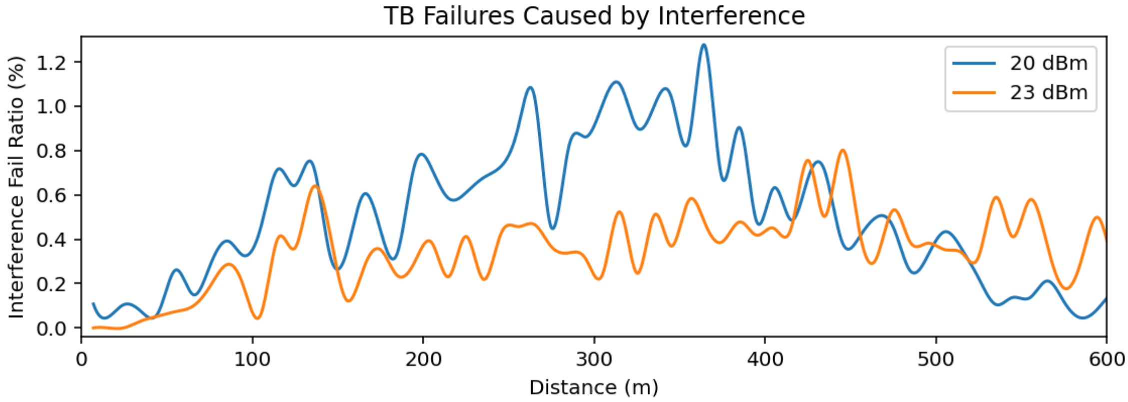

Figure 4.42 TB Failures Caused by Interference – Transmission Power (Fast Highway Scenario)

Let's move to the initial hypothesis where it has been stated that the main reason of this difference at distances beyond 300 m are due to SCI unsensed. Having a look at **Figure 4.43** where the SCI unsensed ratio is plotted against the distance, the hypothesis can be confirmed. The formula that provides the probability of receiving correctly a packet (i.e. the SCI) depends directly on the local average power which depends on the transmission power. For a given distance, with 20 dBm of transmission power is more probable to not receive the SCI than with 23 dBm. This fact is reflected in the plot by having a higher SCI unsensed ratio with 20 dBm.

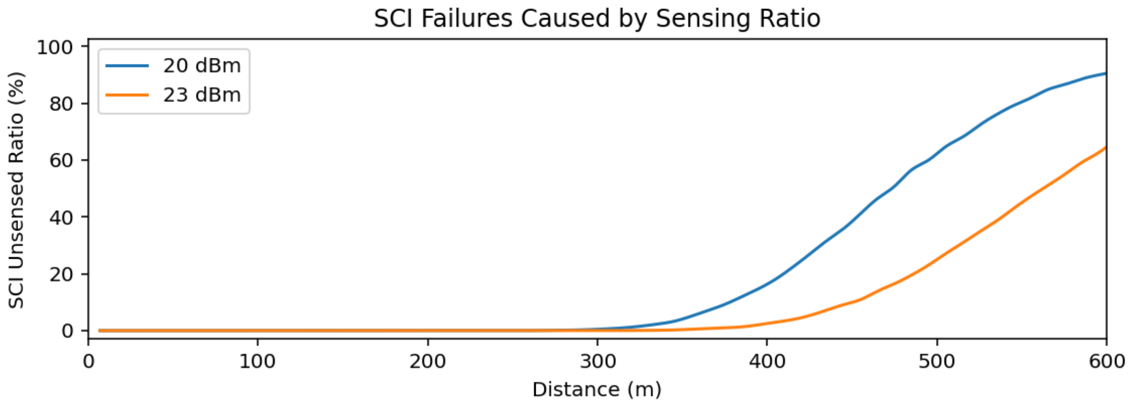

Figure 4.43 SCI Failures Caused by Sensing Ratio – Transmission Power (Fast Highway Scenario)

Congested Highway Scenario

When increasing the vehicle traffic density, the behaviour of the network is very similar. Nothing has changed with respect to the SCI unsensed ratio, since the transmission powers are the same one and this type of error does not depend on the vehicle traffic density or its consequences. However, first of all the PDR will be analyzed and after that the TBs errors caused by interference and/or collision will be analyzed.

In **Figure 4.44** the PDR against the transmission distance is represented for both transmission powers. In this case the difference between both transmission powers is being manifested at similar distances as the ones observed in the fast highway scenario.

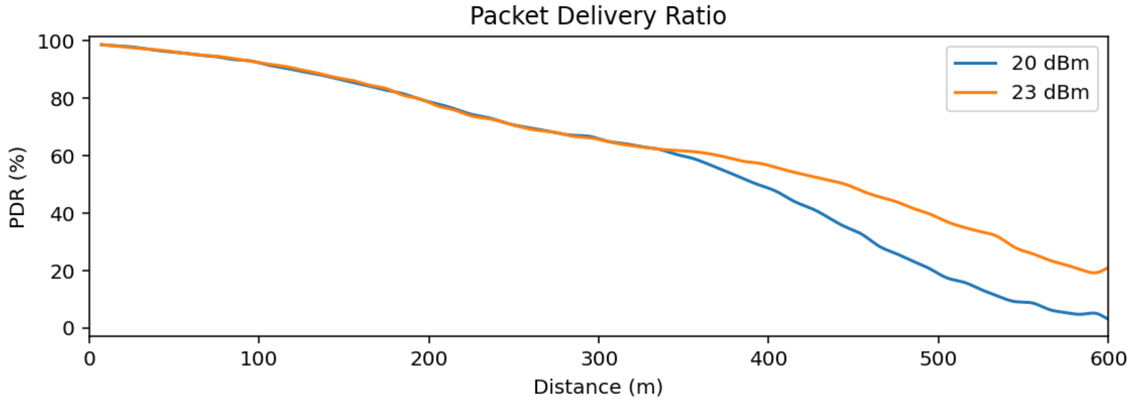

Figure 4.44 PDR vs Distance – Transmission Power (Congested Highway Scenario)

Before going to the conclusions of this section, an analysis of the interference fail type when receiving a TB is going to be carried out **(Figure 4.45)**. At distances between transmitter and receiver higher than 400 m, the difference between the interference fail ratio for 20 and 23 dBm becomes representative. The point here is that for 23 dBm the failures caused by interference are higher than the 20 dBm case. This is mainly by two reasons. The first one is that at such far distances, the main problem becomes the sensing ratio and the majority of the SCIs and consequently the TBs are not received by distance reasons. The second one, is related with that one and has to do with the propagation effects. The packet transmitted at 20 dBm is received with less power than the 23 dBm one at far distances and it produces less interference to the car which is trying to receive the packet at the same CSR.

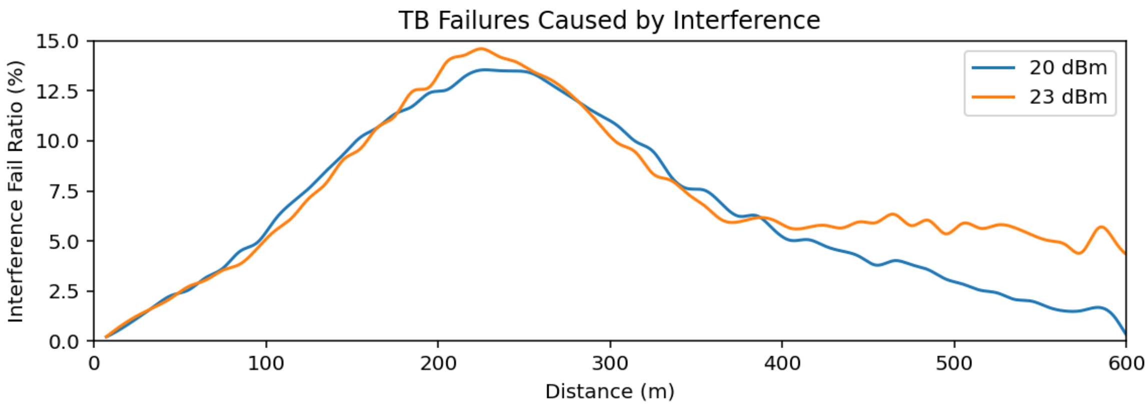

Figure 4.45 TB Failures Caused by Interference – Transmission Power (Congested Highway Scenario)

In a nutshell, the main conclusions that can be extracted from these simulations, is that in case that being necessary to reduce the transmission power from 23 dBm to 20 dBm, there would be no problems since the transmitted data is not relevant at distances higher than 300 m. Even though the performance of the network in terms of PDR starts decreasing at this distance, with 20 dBm the impact is higher and the performance is much worse.

4.6. Speed Effect

The two main scenarios used during this analysis are the fast highway and congested highway scenarios. The first one intends to represent a fast highway with a speed limit of 140 km/h. However, another scenario has been defined in **Section 3.3** named as “minor road” which considers exactly the same traffic conditions in terms of vehicle traffic density as the fast highway but it halves the speed to 70 km/h. The main purpose of this section is to check if changing the speed limit without changing the vehicle traffic conditions will produce any type of variation in terms of average CBR and/or PDR. To do so, the same transmission rates considered in **Section 4.1** (i.e. 1 pps, 2 pps, 5 pps, 10 pps, 20 pps and 50 pps) are used for this speed analysis where the fast highway and minor road scenarios are confronted.

In **Figure 4.46** the average CBR against the transmission rate for fast highway and minor road scenarios. The average CBR curves are very similar for both scenarios and there is a very little difference at 20 and 50 pps with a CBR 2% higher for the minor road scenario which is not relevant at all. The definitive test to know if the network performance is similar for both scenarios is the PDR. In **Figure 4.47** the PDR is plotted against the distance between transmitter and receiver for transmission rates of 10, 20 and 50 pps for both scenarios. For sake of simplicity and figure clarity, 1, 2 and 5 pps transmission rates were omitted. The performance of both scenarios is very similar with small differences mainly caused by the simulation itself rather than related specifically with the speed of the vehicles.

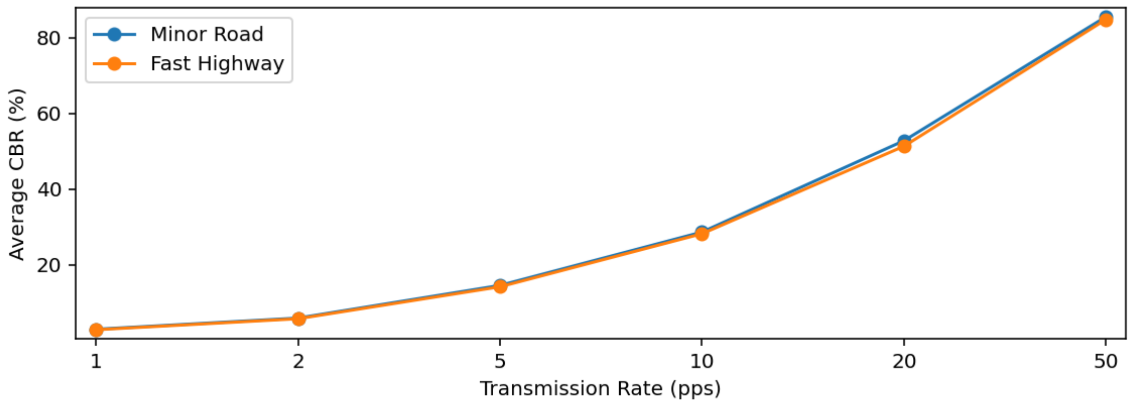

Figure 4.46 Average CBR vs Transmission Rate – Speed Effect

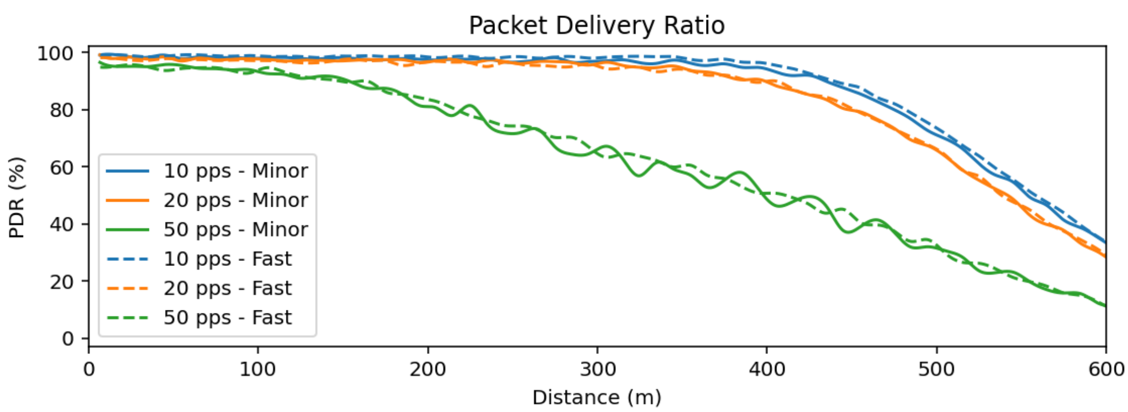

Figure 4.47 PDR vs Distance – Speed Effect

The hypothesis initially raised that the speed would have an impact on the performance of the network could not be demonstrated with the results obtained. However, these results are for a specific sidelink and sensing-based SPS configuration and also a QPSK modulation. To get insights of the real impact of the speed, it would be interesting in future works, to iterate over different MCS, and channel configurations to see how the performance of the network varies. In addition, different traffic densities could be checked with different scenarios where only the speed varies. Then it can be stated that with the configuration and the vehicle traffic conditions defined to analyze the speed impact, changing the vehicles speed from 140 km/h to 70 km/h, has no relevant impact on the network performance.

4.7. Congestion Control – Packet Dropping

The study of the transmission frequency and its implications on the performance of the network **(Section 4.1)**, revealed that especially for the congested highway scenario the congestion of the channel in terms of CBR was very high. The LTE-V Mode 4 provides two metrics such as CBR and CR to measure the channel congestion, however it proposes some possible congestion control mechanisms without specifying a specific one as the recommended. In **Section 2.3.2**, these proposed congestion control mechanisms were described. In this section, the intention is to analyze which is the impact over the overall system when a congestion control mechanism such as packet dropping is implemented. Even though the standard allows each vehicle to select their own congestion control mechanism, in the studied case, all the vehicles in the simulation will implement the same one and will drop certain packets generated by the application to reduce its CR based on the CBR intervals and CR_{LIMIT} table defined in **Table 3.3**. The final intention is to reduce the CBR to reduce also the congestion of the channel and increase the PDR of the overall system. A detailed analysis of the packet dropping mechanism used has been carried out in **Section 2.3.2.1**.

The analysis of the impact of applying packet dropping on CBR is shown in **Figure 4.48** where the average CBR is plotted against the transmission rate for the fast and congested highway scenarios with and without packet dropping. From now, packet dropping may be also referred as PD.

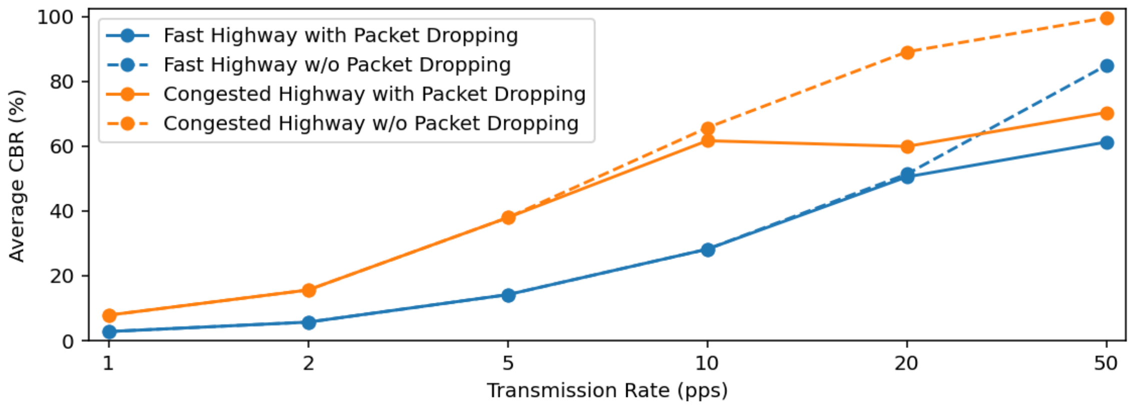

Figure 4.48 Effect of Packet Dropping on CBR

The table with the CBR intervals and CR_{LIMIT} used in these simulations is taken from the 3GPP working documents [5]. This table was proposed for transmission rates of 10 pps and they suggested that should be modified for 20 or 50 pps. In this work, it has been decided to use the same table for all the transmission rates as it was the unique reliable table that has been found. Giving a glance at **Figure 4.48**, the packet dropping mechanism only operated for transmission rates higher than 10 pps. In fact, at the fast highway scenario, the packet dropping mechanism was not necessary for 10 pps and with 20 pps the improvement is very little.

To assess quantitatively how much does the CBR improve in **Table 4.2** the improvement on average CBR with packet dropping is represented.

Table 4.2 Improvement on Average CBR with Packet Dropping

	Fast Highway			Congested Highway		
Periodicity	**w/o PD**	**with PD**	**Improvement**	**w/o PD**	**with PD**	**Improvement**
10 pps	28.20 %	28.20 %	0 %	65.65 %	61.65 %	6.099 %
20 pps	51.34 %	50.49 %	1.66 %	89.06 %	59.89 %	32.75 %
50 pps	84.88 %	61.24 %	27.85 %	99.57 %	70.36 %	29.34 %

Note that 1, 2 and 5 pps transmission rates were omitted for sake of simplicity since no improvement was detected. It can be confirmed that the improvement with the vehicle traffic density of the fast highway is only relevant at 50 pps. However, when considering the congested highway scenario, there is a relevant improvement from 10 pps onwards. In addition to the channel congestion, also the effect on the packet dropping rate needs to be analyzed. To do so, the dropping rate has been defined as the average dropped packets by all the vehicles in the simulation divided by the average generated packets by all vehicles. In **Table 4.3** the packet dropping rate is represented for both scenarios and transmission rates higher than 10 pps.

Table 4.3 Packet Dropping Rate

	Fast Highway			Congested Highway		
Periodicity	**Gen. Packets**	**Dropped Packets**	**Dropping Rate**	**Gen. Packets**	**Dropped Packets**	**Dropping Rate**
10 pps	115.55	0	0 %	115.51	4.452	3.85 %
20 pps	230.58	1.303	0.565 %	230.52	96.50	41.86 %
50 pps	575.85	226.21	39.28 %	575.56	323.82	56.26 %

Having a look at the congested highway section of **Table 4.3**, it is relevant to mention that for 20 and 50 pps, the “real” transmission rate is almost half of the initially intended one. Considering 50 pps, more than half of the packets are dropped, providing a very similar rate as the 20 pps without packet dropping but with smaller CBR.

Fast Highway Scenario

The CBR is reduced by implementing packet dropping. This reduction should result in a better performance. A dropped packet is considered as not transmitted, therefore the PDR does not take into account this packet as a failure at reception. The PDR is represented for 10, 20 and 50 pps with and without packet dropping mechanism against the transmission distance in **Figure 4.49**. Taking a glance at the plot, the first fact that surprises is that for 50 pps, the PDR is lower than the case without packet dropping. At 20 pps the performance is very similar whereas for 10 pps it is the same one since there were no packets dropped. There are two reasons that affect to the PDR when introducing the packet dropping. The first one is directly related with the CBR and CR_{LIMIT} table used **(Table 3.3)**. As mentioned at the beginning of the section, this table was designed to be used with transmission rates of 10 pps.

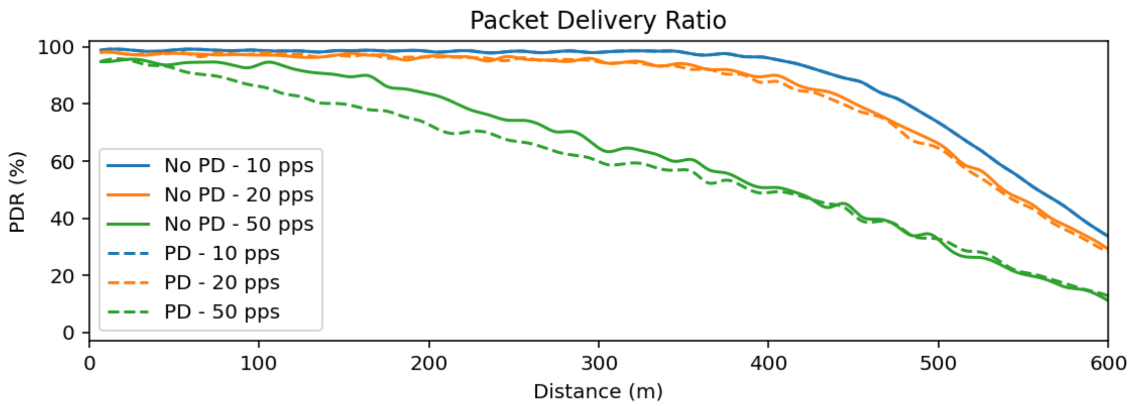

Figure 4.49 PDR vs Distance – Packet Dropping (Fast Highway Scenario)

When introducing transmission rates of 20 and 50 pps the RRI, RC and selection window change. Thus the first reason is that the Table 3.3 may not be very accurate for values different from 10 pps because even though reduces the channel congestion, which is the main purpose of packet dropping, it also reduces the PDR. The second and main reason is that the number of TBs that fail to be decoded caused by interference or collision is higher as it can be observed in **Figure 4.50**. In this plot the TB interference fail ratio is represented for 10, 20 and 50 pps with and without packet dropping against the transmission distance.

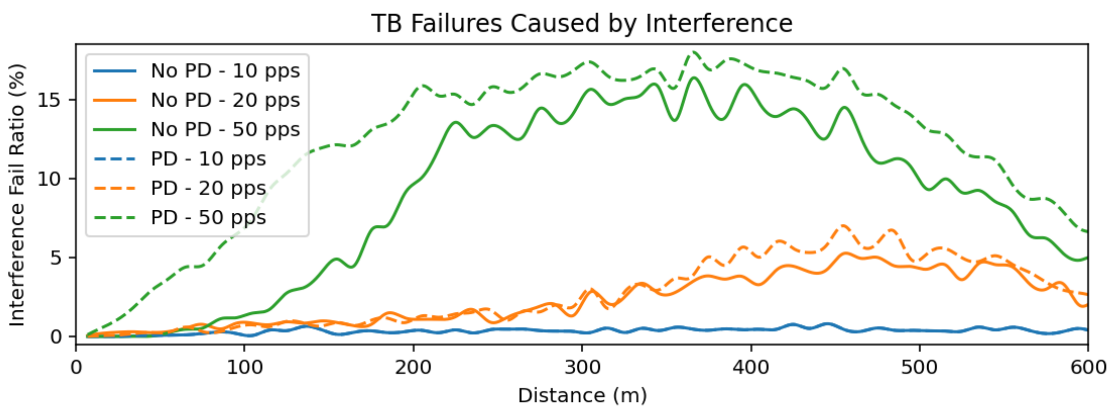

Figure 4.50 Interference Fail Ratio – Packet Dropping (Fast Highway Scenario)

The interference fail ratio is higher for the case where the packet dropping mechanism is applied. This effect may be caused by the “reselect after” parameter. In this simulation, as mentioned in **Table 3.1**, it takes value 1, forcing to select new resources every time a packet is dropped and degrading the quality of the available CSRs.

Congested Highway Scenario

Now, the analysis of the PDR when simulating under a very demanding scenario in terms of vehicle traffic density such as the congested highway scenario is going to be carried out. In this scenario, as seen in **Table 4.3**, the packet dropping ratio is higher than the fast highway scenario, as do the channel congestion. In **Figure 4.51**, the PDR against the transmission distance between transmitter and receiver is represented for transmission rates of 10, 20 and 50 pps, with the packet dropping mechanism enabled and disabled.

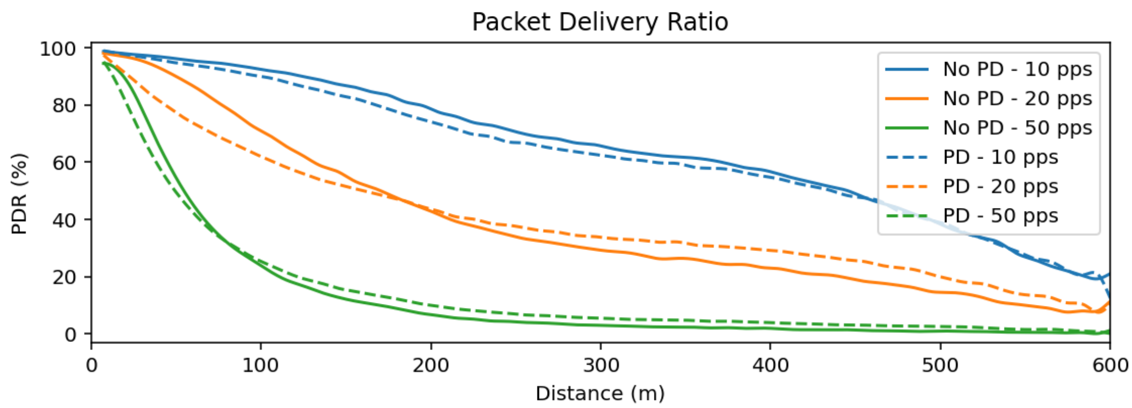

Figure 4.51 PDR vs Distance – Packet Dropping (Congested Highway Scenario)

In this case, there is a difference with respect to the fast highway case. For 10 pps, the packet dropping reveals worse performance than without applying it. However for 20 and 50 pps, the packet dropping improves the PDR from distances beyond 200 m and 80 m respectively. As done in the fast highway case, the TB failures caused by interference and/or collision has been plotted for 10, 20 and 50 pps with and without congestion control mechanism in **Figure 4.52**.

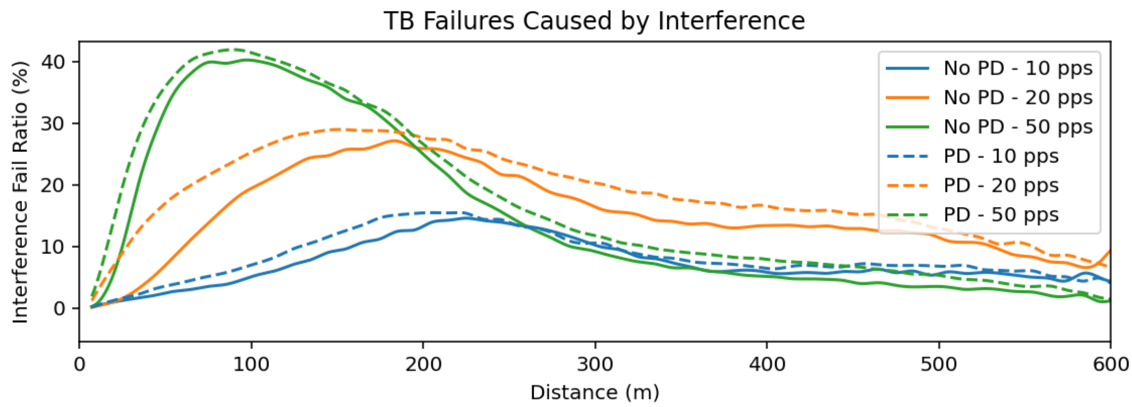

Figure 4.52 Interference Fail Ratio – Packet Dropping (Congested Highway Scenario)

In that case, as it has happened in the fast highway scenario, due to probably the same reason, the packet dropping mechanism increases the PDR in all the range of distances.

However, at the PDR plot, as mentioned before, the packet dropping mechanism offers better performance beyond a given distance. The unique that can counteract the extra TB interference fail ratio that packet dropping produces, it is the SCI interference fail ratio. In **Figure 4.53** the SCI interference fail ratio is represented against the transmission distance. In this figure, it can be observed how applying the packet dropping reduces the number of TB decoding failures because the associated SCI has not been received. For that vehicle channel congestion it seems that the packet dropping helps at large distances.

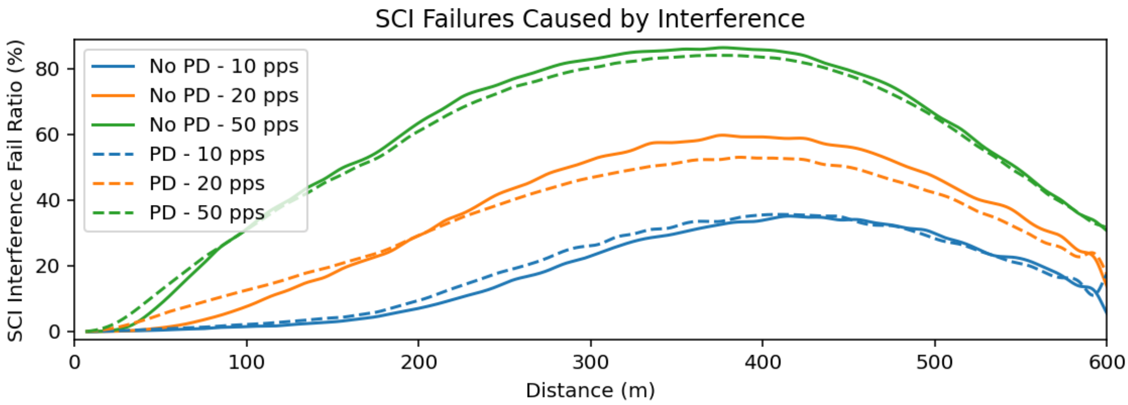

Figure 4.53 SCI Interference Fail Ratio – Packet Dropping (Congested Highway Scenario)

This section has revealed interesting and surprising results. The first question that must be done is, which benefit did the network experience by reducing the CBR? For the fast highway scenario, reducing considerably the channel congestion did not improved the PDR whereas for the congested scenario the improvement was negligible. No benefits at all were observed when implementing congestion control. The first impression after the analysis carried out at **Section 2.3.2.1** and the results obtained, is that packet dropping is not a suitable congestion control mechanism for C-V2X Mode 4, mainly because of its sensing-based SPS for reserve resources to transmit. In further works it would be interesting to check this mechanism under more demanding scenarios, check different “reselect after” values and even check with other CBR and CR_{LIMIT} table more suitable for 20 and 50 pps.

At the moment, there are some papers where the packet dropping mechanism is analyzed which reveal very similar results to the ones obtained in this thesis. In [6] the approach without sending the associated SCI to the dropped packet is carried out with very similar results, the CBR being reduced but the PDR falls apart because the resources are shown as fully free. Anyway, this solution and the one adopted in this thesis shows that packet dropping in the way it is described is not a good solution for congestion control. More elaborated congestion control mechanisms and its impact to the network are analyzed in [20], revealing surprising improvements on PDR especially for very high vehicle density scenarios.

5. Conclusions and future development

The C-V2X Mode 4 or LTE-V Mode 4 standard has been designed to improve the safety driving conditions by means of V2V communications. It is a suitable technology for transmission of small awareness and information messages when the vehicles are out of cellular coverage or under cellular coverage. However, it becomes relevant when the vehicles are out of coverage since only this mode can be used in that situation.

The main objective of this thesis has been to provide a theoretical study of C-V2X Mode 4 and analyze its performance in terms CBR, PDR, delay and main causes of transmission failures under different scenarios and different channel configurations. Some of the extracted conclusions from this thesis are listed below.

- The results have revealed that the transmission rate has an important influence especially on the PDR. Increasing the transmission rate reduces the PDR, this is caused mainly by the number of reception errors caused by the interference/collision of the packet. In addition, under the congested scenario the PDR decreases considerably for transmission rates higher than 10 pps. In addition, the CBR experienced increases as the transmission rate and vehicle traffic density do.
- The vehicles have a certain probability of keeping the granted resources after the RC has reaches zero. However, the impact of changing this value has only revealed significant variations when the vehicle traffic density is high. In that case, forcing the vehicle to select always new resources decreased the PDR. In this case, the assignation of new resources more frequently implies degrading the quality of the selected resources and increasing the potential interferences and/or collisions.
- LTE-V Mode 4 considers modulations such as QPSK, 16QAM and even 64QAM at its latest releases. When the modulation has been increased and therefore the data protection has been reduced, a better overall performance has been observed in terms of PDR and CBR. This should be tested under scenarios not limited by capacity to check if at large distances the QPSK modulation becomes more reliable as initially expected.
- Modifying the packet size and subchannelization scheme has led to surprising results. Some subchannelizations may have equal results in terms of PDR depending on the scheme and the selected packet size. Then, it is important to try to maximize the efficiency of the allocation by selecting appropriately the subchannelization scheme given an MCS and packet size.
- Transmitting at 20 dBm instead of 23 dBm, if necessary, provides very similar performance at transmission distances below 300 m for both scenarios. Nevertheless, at distances beyond this point, the probability of sensing a packet with 20 dBm decreases faster than the 23 dBm case.
- The fast highway scenario considered vehicles top speed of 140 km/h. The performance of a scenario with the same characteristics but a top speed of 70 km/h has been tested with no relevant differences in terms of PDR or CBR.
- Finally, the last simulations were intended to check the impact of applying congestion a control mechanism such as packet dropping. As initially expected, the

CBR was reduced when applying packet dropping, however, the PDR has been also reduced. The fact that the considered implementation of packet dropping is not a suitable congestion control mechanism for C-V2X Mode 4 due to its resource reservation protocol becomes a real possibility. Studies with similar results can be found in [6] whereas more sophisticated congestion control mechanisms with an improvement in terms of PDR at very high vehicle density scenarios are discussed in [20].

A general analysis of different key parameters of the technology has been carried out in this thesis. There are some analysis points which led to new questions about the technology and also other configurations that were not studied by lack of time. A list of future works and research lines is listed below.

- The investigation of new scenarios would be a good research line. Changing the main characteristics of the road such as the number of lanes to increase the number of vehicles, increase even more the vehicle traffic density for ultrahigh density-like urban scenarios with more than 100 vehicles/km·lane or introduce a Manhattan grid scenario with buildings are some ideas.
- During the whole work, adjacent PSCCH-PSSCH scheme has been considered for sake of simplicity. A research line where a similar study to the one that concerns this work but with the non-adjacent scheme, would be of interest too
- The latency requirement specified during the thesis was always determined by the transmission rate. Force different latency constraints to check the response of the network would be a good idea too.
- Incorporate a second application with different requirements and packet size would affect the behaviour of the application. Managing different subchannelization schemes for each application or choosing one for both applications would be an interesting discussion-
- .A collaboration with the developer of the C-V2X Mode 4 implementation to program all the enhancements considered in the V2X phase 2 such as carrier aggregation, resource sharing or transmit diversity to improve the PDR specially in demanding scenarios in terms of vehicle and packet traffic. In addition, the introduction of the 5G NR Sidelink should be considered to check the improvement with respect to the LTE-V Sidelink. This, should definitely cope with the observed problems with respect to PDR and CBR when considering demanding scenarios in terms of vehicle and packet traffic.

Bibliography

[1] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an International Standard for Wireless Access in Vehicular Environments," VTC Spring 2008 - IEEE Vehicular Technology Conference, Singapore, 2008, pp. 2036-2040, doi: 10.1109/VETECS.2008.458.

[2] 3GPP, "Release description; Release 14 (v14.0.0, Release 14)", 3GPP, Tech. Rep. 21.914, June 2018.

[3] 3GPP, "Study on LTE support for Vehicle-to-Everything (V2X) services (v14.0.0, Release 14)", 3GPP, Tech. Rep. 22.885, December 2015.

[4] 3GPP, "Proximity-based services (ProSe); Stage 2 (v12.8.0, Release 12)", 3GPP, Tech. Rep. 23.303, March 2016.

[5] Qualcomm Incorporated, "R1-1611594. Congestion control for V2V," presented at 3GPP TSG RAN WG1 Meeting #87, Reno, NV, Nov. 2016.

[6] A. Mansouri, V. Martinez and J. Härri, "A First Investigation of Congestion Control for LTE-V2X Mode 4," 2019 15th Annual Conference on Wireless On-demand Network Systems and Services (WONS), Wengen, Switzerland, 2019, pp. 56-63, doi: 10.23919/WONS.2019.8795500.

[7] 3GPP, "Release description; Release 15 (v15.0.0, Release 15)", 3GPP, Tech. Rep. 21.915, Sep. 2019

[8] S. Lien et al., "3GPP NR Sidelink Transmissions Toward 5G V2X," in IEEE Access, vol. 8, pp. 35368-35382, 2020, doi: 10.1109/ACCESS.2020.2973706.

[9] Sommer, C. (2006). Veins. Retrieved June 9, 2020, from https://veins.car2x.org/

[10] OpenSim Ltd. (2001). OMNeT++ Discrete Event Simulator. Retrieved June 9, 2020, from https://omnetpp.org/

[11] German Aerospace Center (DLR) and others. (2001). Simulation of Urban MObility (SUMO). Retrieved June 9, 2020, from https://sumo.dlr.de/docs/index.html

[12] OpenSim Ltd. (2006). INET Framework - INET Framework. Retrieved June 9, 2020, from https://inet.omnetpp.org/

[13] Virdis, A., & Nardini, G. (2016). SimuLTE - LTE User Plane Simulation Model for INET & OMNeT++. Retrieved June 9, 2020, from https://simulte.com/

[14] Science Foundation Ireland (SFI), & McCarthy, B. (2019). OpenCV2X Mode 4. Retrieved June 9, 2020, from http://www.cs.ucc.ie/cv2x/

[15] OpenSim Ltd. (2019). OMNeT++ Tutorials – Learn OMNeT++ with TicToc. Retrieved June 30, 2020, from https://docs.omnetpp.org/tutorials/tictoc/

[16] Varga, András & Hornig, Rudolf. (2008). An overview of the OMNeT++ simulation environment. 60. 10.1145/1416222.1416290.

[17] 3GPP, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (v 14.14.0, Release 14)", 3GPP, Tech. Spec. 36.213, March 2020.

[18] S. Krauss, "Microscopic modeling of traffic flow: Investigation of collision free vehicle dynamics," D L R - Forschungsberichte, no. 8,1998.

[19] J. Song, Y. Wu, Z. Xu and X. Lin, "Research on car-following model based on SUMO," The 7th IEEE/International Conference on Advanced Infocomm Technology, Fuzhou, 2014, pp. 47-55, doi: 10.1109/ICAIT.2014.7019528.

[20] B. Toghi, M. Saifuddin, Y. P. Fallah and M. O. Mughal, "Analysis of Distributed Congestion Control in Cellular Vehicle-to-Everything Networks," 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 2019, pp. 1-7, doi: 10.1109/VTCFall.2019.8891335.

Glossary

3GPP: Third Generation Partnership Project

5G NR: Fifth Generation New Radio

CA: Carrier Aggregation

CBR: Channel Busy Ratio

CR: Channel occupancy Ratio

CSR: Candidate Single-Subframe Resource

C-V2X: Cellular Vehicle to Everything

D2D: Device to Device

DMRS: De-Modulation Reference Signals

DSRC: Direct Short Range Communications

eNB: evolved Node B

E-UTRAN: Evolved UMTS Terrestrial Radio Access Network

eV2X: enhanced Vehicle to Everything

LTE: Long Term Evolution

LTE-V: LTE-Vehicular

MCS: Modulation and Coding Scheme

NED: NEtwork Description

NIC: Network Interface Card

OSI: Open Systems Interconnection

PPS: Packets per Second

ProSe: Proximity Services

PD: Packet Dropping

PDR: Packet Delivery Ratio

PDSCH: Physical Downlink Shared Channel

PSCCH: Physical Sidelink Control Channel

PSSCH: Physical Sidelink Shared Channel

PUSCH: Physical Uplink Shared Channel

QAM: Quadrature Amplitude Modulation

QPSK: Quadrature Phase-Shift Keying

RB: Resource Block

RC: Reselection Counter

RRI: Resource Reservation Interval

RSRP: Reference Signal Received Power

RSSI: Received Signal Strength Indicator

SC-FDMA: Single Carrier – Frequency Division Multiple Access

SCI: Sidelink Control Information

SINR: Signal to Interference and Noise Ratio

SL: Sidelink

SNR: Signal to Noise Ratio

SPS: Semi Persistent Scheduling

SRS: Sounding Reference Signal

SUMO: Simulation of Urban Mobility

TB: Transport Block

UE: User Equipment

V2I: Vehicle to Infrastructure

V2N: Vehicle to Network

V2P: Vehicle to Pedestrian

V2V: Vehicle to Vehicle

V2X: Vehicle to Everything